Radio Science Techniques and Investigations

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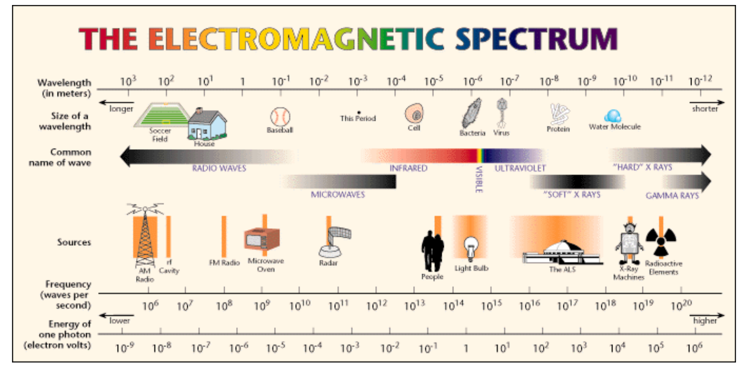
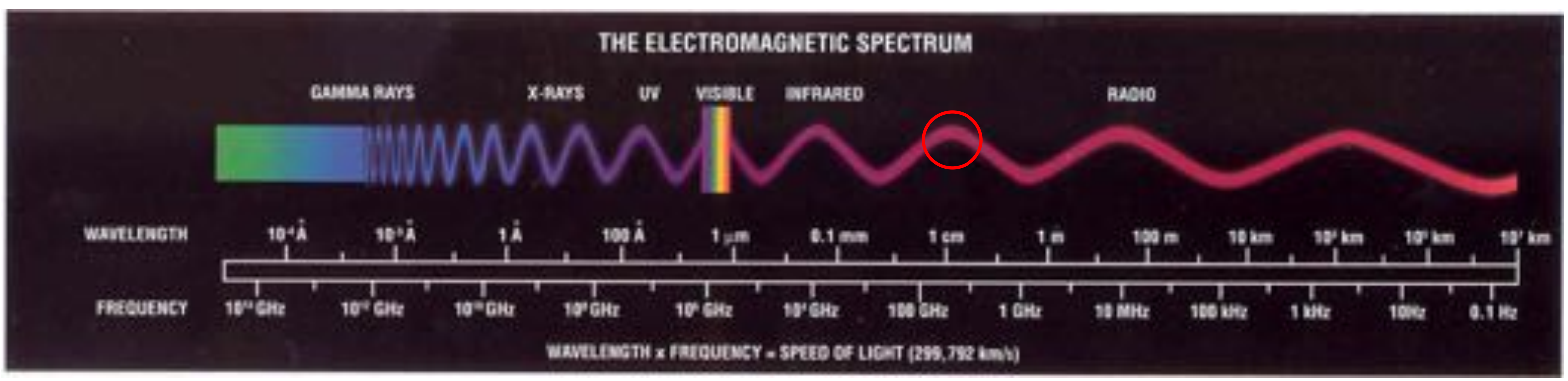
Sardinia Seminar Series

17-21 June 2019

Radio Signals: Cell Phones to Deep Space

- International Telecommunications Union is UN treaty organization charged with maintaining law and order in the use of the electromagnetic spectrum
- Communications bands categorized by Near Earth & Deep Space
  - Propagation effects (effect of media)
  - Communications performance (number of bits)
  - Evolving technologies (miniaturizing, power consumption)
- Three bands currently used by Deep Space network (S, X, & Ka)
  - S-band uplink in increasing conflict with cell phone usage
  - UHF from probe proximity links

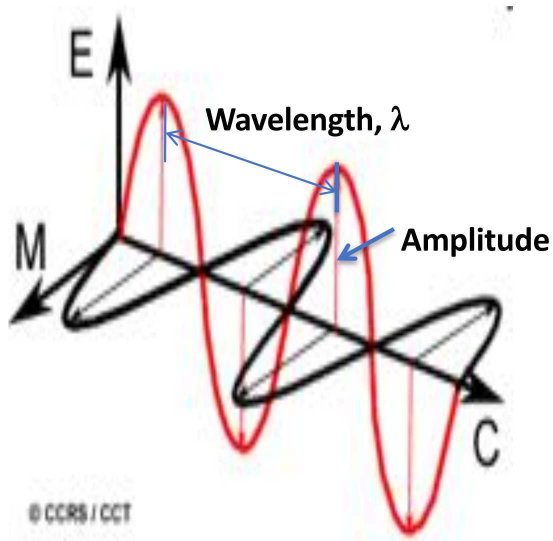


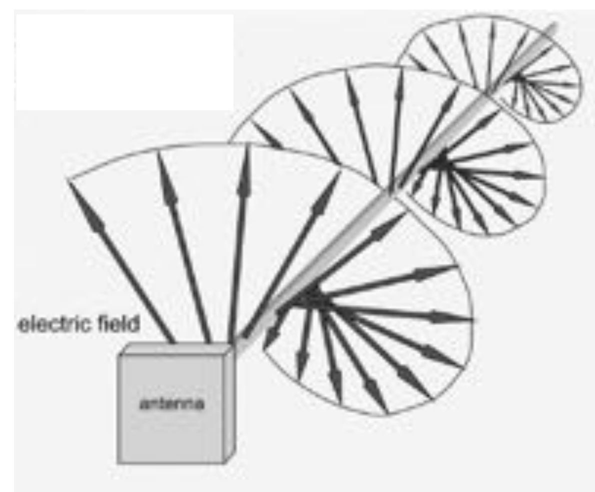


Electromagnetic Waves

- Wave: energy moving through a medium
- Water waves: energy moves through water
- Sound: energy moves through air and matter
- Earthquakes: seismic energy moves through matter

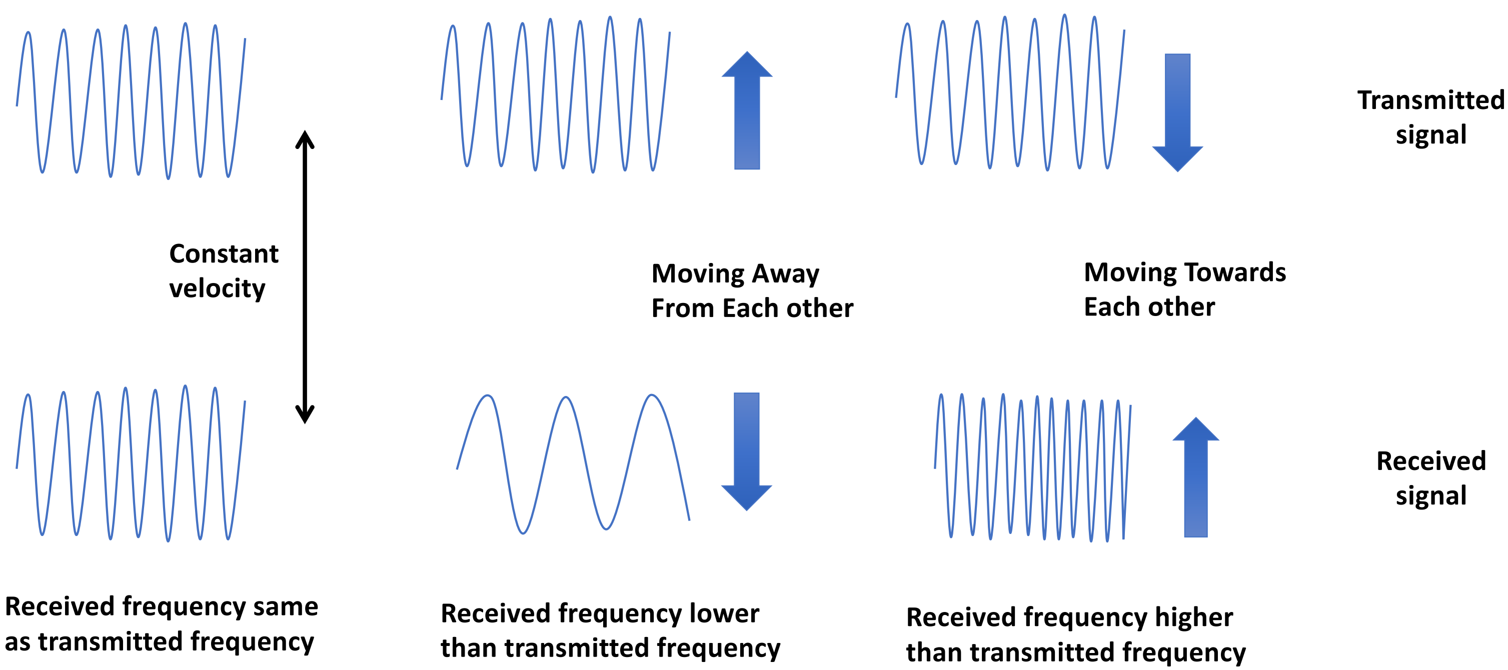
- Electromagnetic: energy moves through a vacuum and some matter
- When the electric field oscillates around the propagation vector (oscillating through both planes in a corkscrew effect), the signal is circularly polarized.





The Doppler Effect

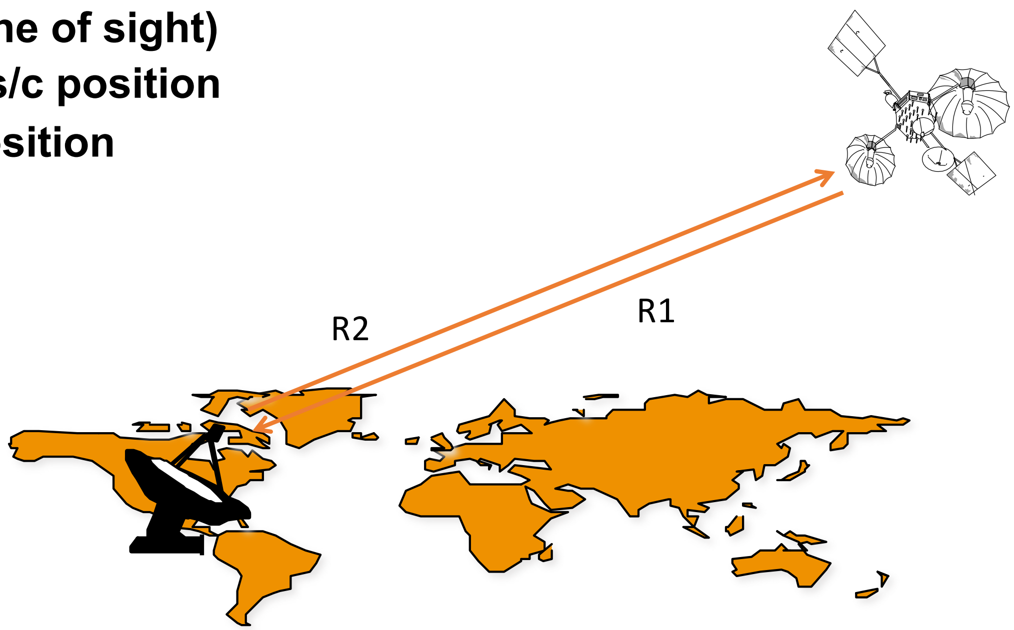
- **Observed change in the frequency of a radio wave due to the relative velocity between transmitter and receiver**
- **Doppler is range rate**
- **Doppler Effect changes observed frequency in motion**
  - **Approaching sources appear to transmit higher frequencies**
  - **blue shift**
  - **Receding sources appear to transmit lower frequencies**
  - **red shift**
- **Measuring radio frequency from spacecraft allows us to determine the relative line-of-sight velocity**



Spacecraft Tracking Data

- **Provide spacecraft position and velocity**
  - **Navigators solve current and predicts future state vector**

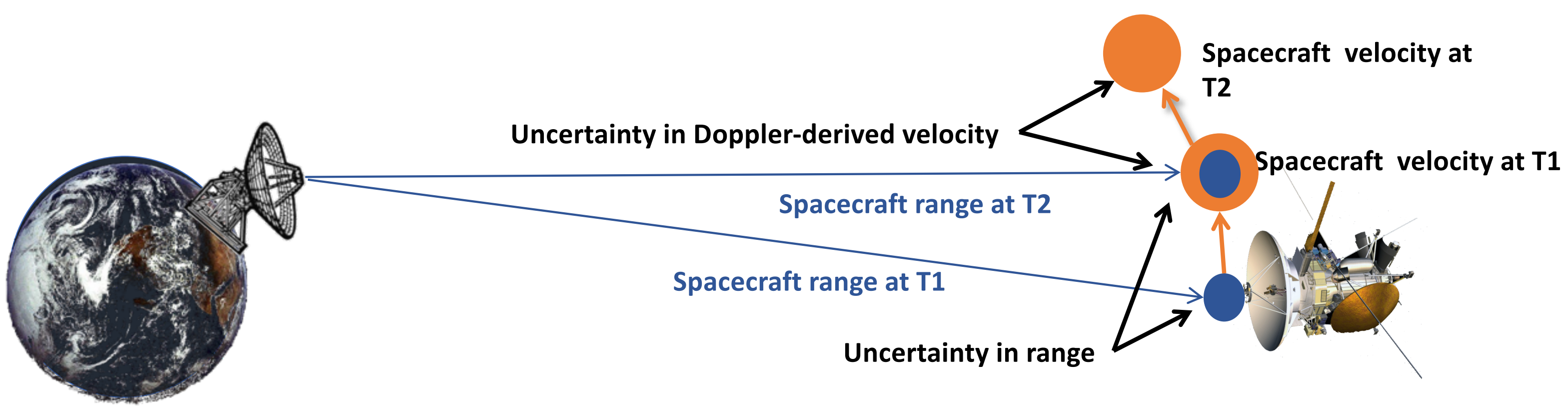
- **Tracking – Finding and following a s/c as it moves**
- **Ranging – Distance to s/c (line of sight)**
- **Doppler – Rate of change in s/c position**
- **VLBI – Spacecraft angular position**



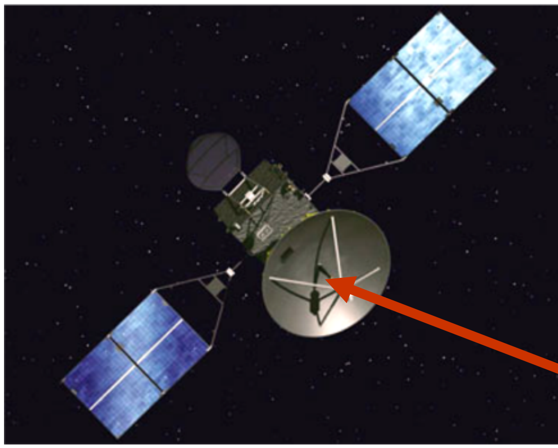
Radiometric Data:
Measurements using the radio signal and and changes in its properties

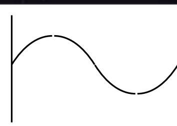
Range and Doppler in the DSN

- DSN receivers always measure spacecraft Doppler (velocity)
  - Range measurements complement Doppler-derived velocity
    - Small errors in velocity, integrated over time, get large
    - Range measurement puts an upper bound on this growth
    - "Doppler only" solution is like using a car's speedometer and driving time to determine location. A better method uses both speedometer (velocity) and odometer (range).

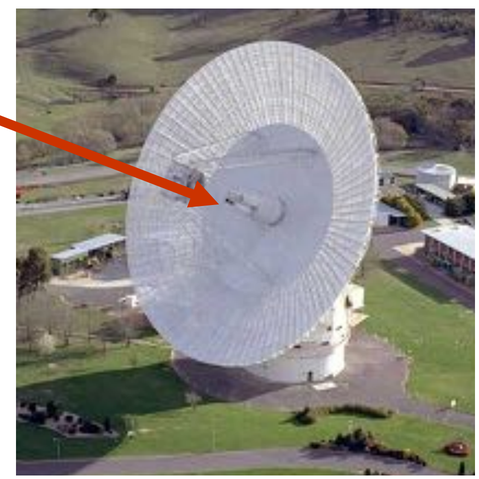


Electromagnetic Wave Communication





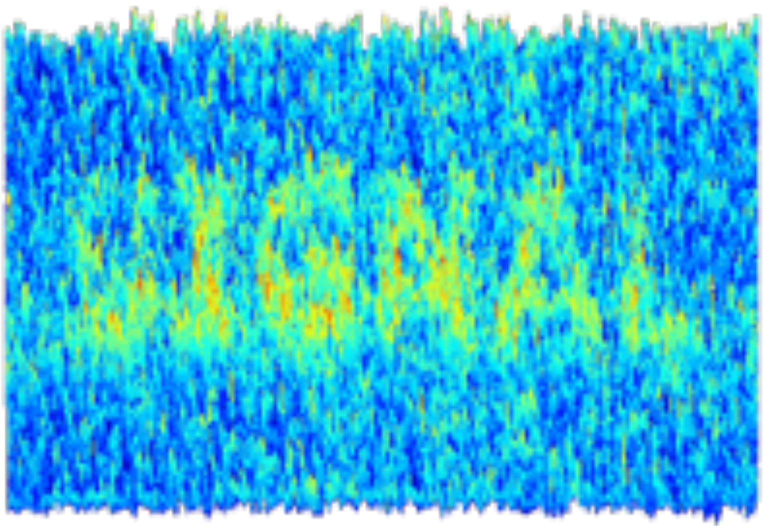
- Spacecraft communications are carried on electromagnetic waves that travel between ground facilities and satellites in space
- These electromagnetic waves travel at the speed of light (3×10^8 m/s through free space)

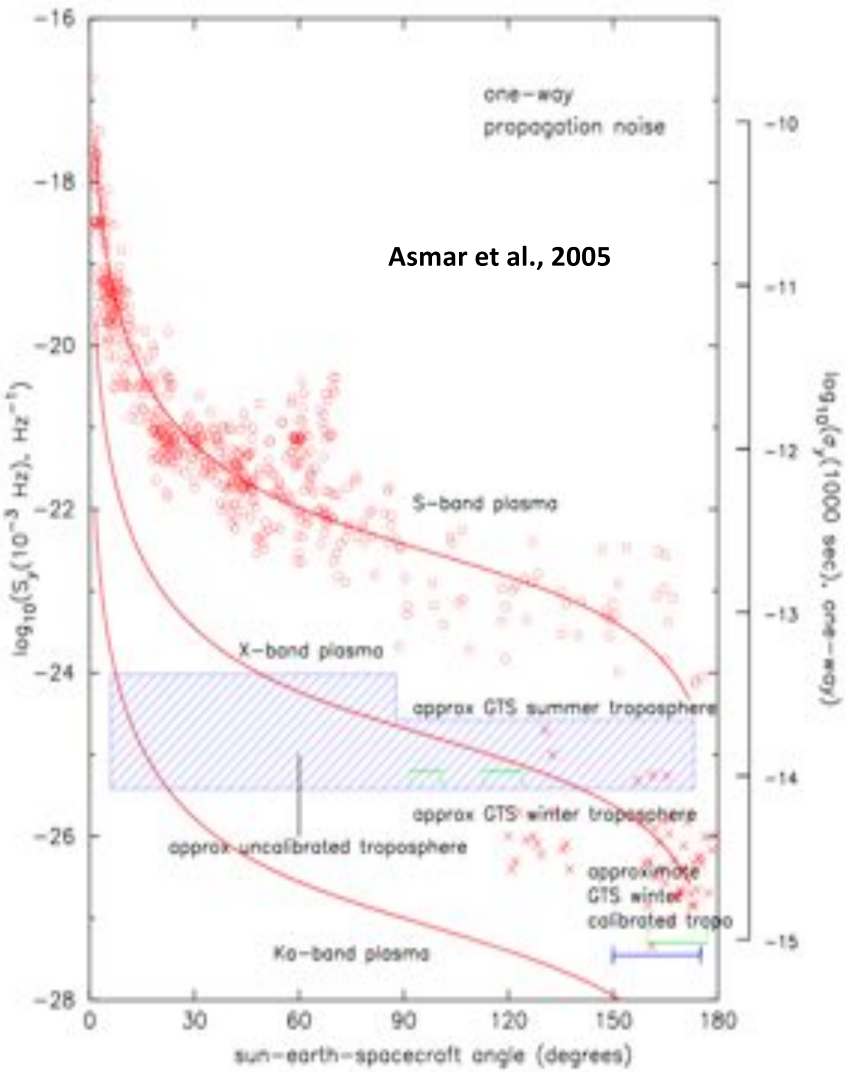


- Electromagnetic waves used for spacecraft communication are generally cm or mm in length
- The wave shown here is 3.6 cm in length, the wavelength of a 8.4 GHz signal

Signal from the Noise

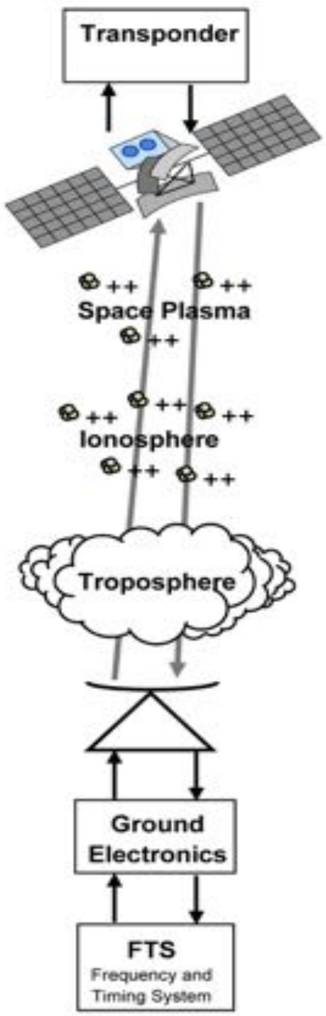
- Noise is additional "signal" not corresponding to information
- Introduces changes in ideal free-space signal; may lead to incorrect interpretation of information at the received signal destination
  - Signal noise
    - Amplitude noise – error in the magnitude of a signal
    - Phase noise – error in the frequency / phase modulation
  - System Noise
    - Component passive noise (heat)
    - Component active noise (amplifiers, mixers, etc…)
  - Environmental Noise
    - Atmospheric ionospheric or precipitation
    - Solar or Galactic
- Radio Frequency Interference (RFI)
  sources on Earth



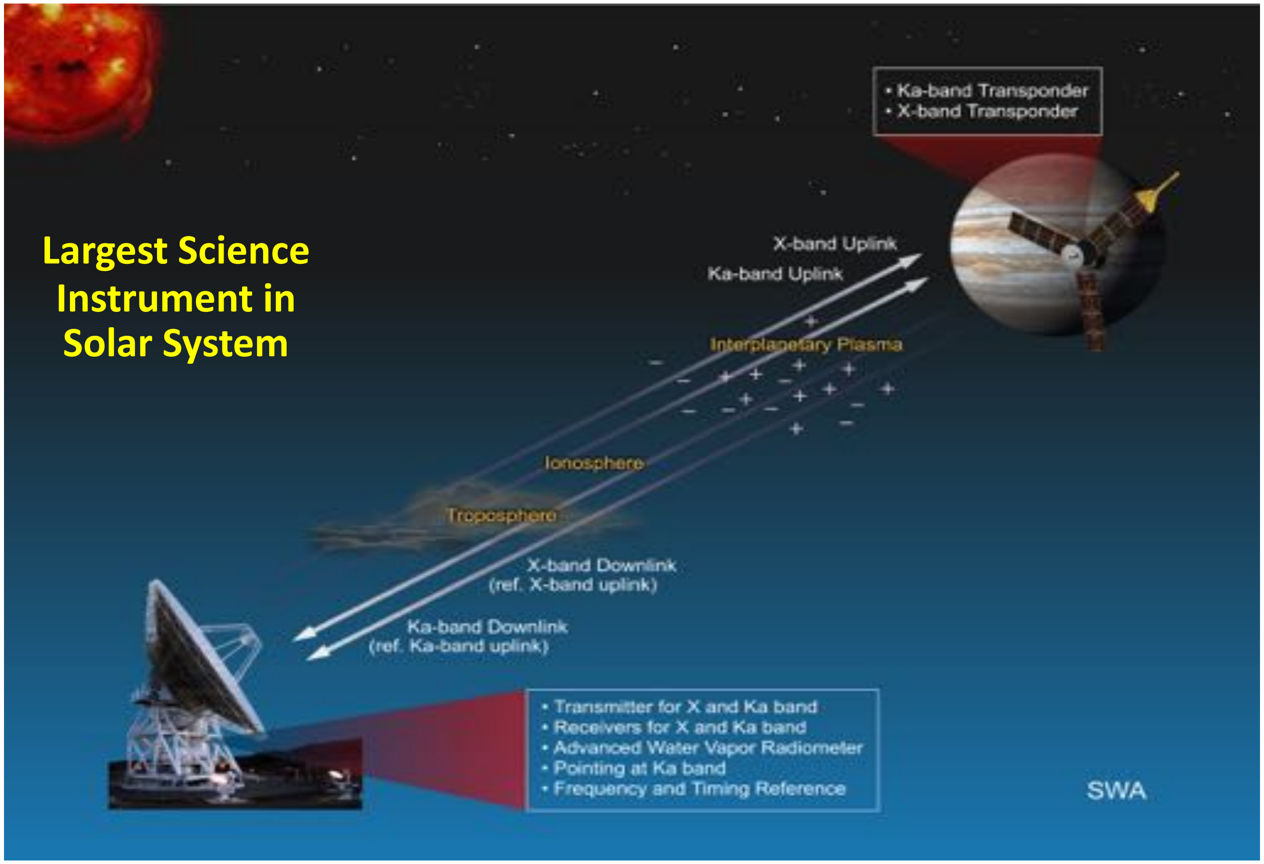


Dispersive Noise

- One-way propagation noise at S-, X-, and Ka-bands as function of angular distance from Sun
- SEP: Sun-Earth-Probe angle
  - 0 degrees at solar conjunction
  - 180 degrees at opposition
- Also shows tropospheric noise which is not dispersive (neutral)



Principle Noise Sources:
Instrumental, Propagation, Systematic



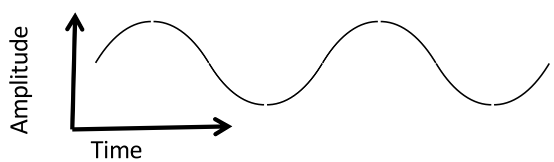
Link Definitions

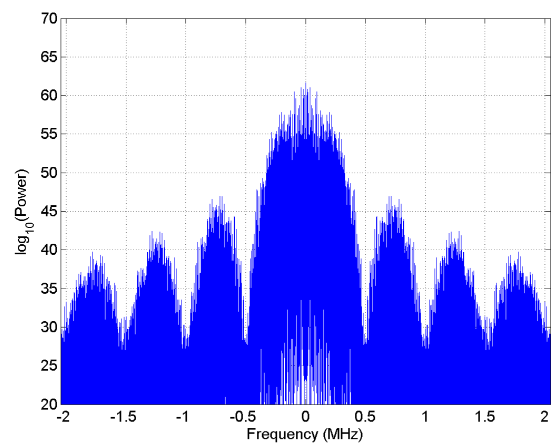
- **Downlink bands (frequencies and wavelengths):**
  - **S-band: ~2.3 GHz ~13 cm**
  - **X-band: ~8.4 GHz ~3.6 cm**
  - **K_a-band: ~ 32 GHz ~1 cm**
- **Uplink frequencies derived via transponder ratio**
- **Relation between bands key to dispersive relations**

Table 3. Channel frequency ratios

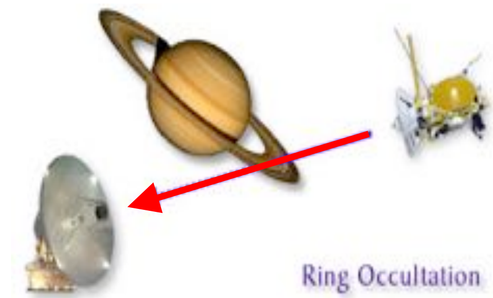
Band pair	Channel frequency ratio
2110-2120 MHz, 2290-2300 MHz	$\frac{221}{240}$
7145-7190 MHz, 8400-8450 MHz	$\frac{749}{880}$
2290-2300 MHz, 8400-8450 MHz	$\frac{3}{11}$

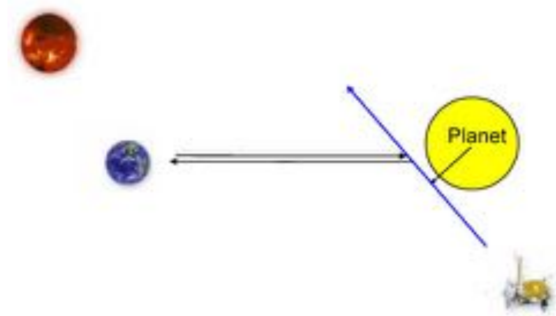
Time and Frequency Domains





Signal Modes





- Coherency Modes
  - **One-way: signal referenced to source onboard spacecraft**
  - **Two-way: downlink coherent with uplink signal**
  - **Three-way: uplink and downlink at different stations**
  - **Four-way: Sometimes used for relay satellites**
- Reception modes
  - **Closed-loop: find, lock-on, and track received signal**
  - **Open-loop: down-convert and record in pre-selected bandwidth using a prediction signal profile**

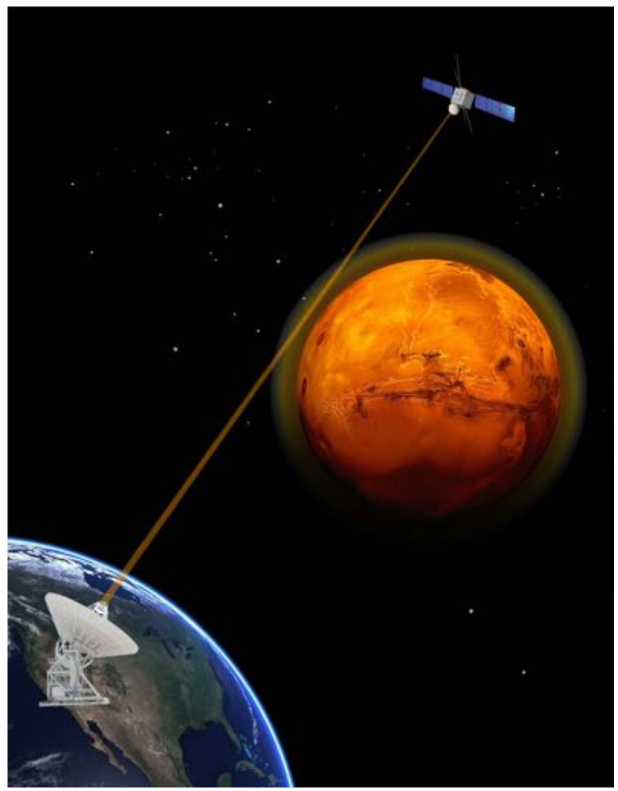
- Decibel **= One-Tenth of a Bel**
- **Bel is the logarithm (base 10) of the ratio between two values (e.g., power, current, voltage)**
- **Operation is addition instead of multiplication**
- **Compute decibels using a power ratio: Decibels (dB) = 10 x $\log_{10}$(P2/P1)**

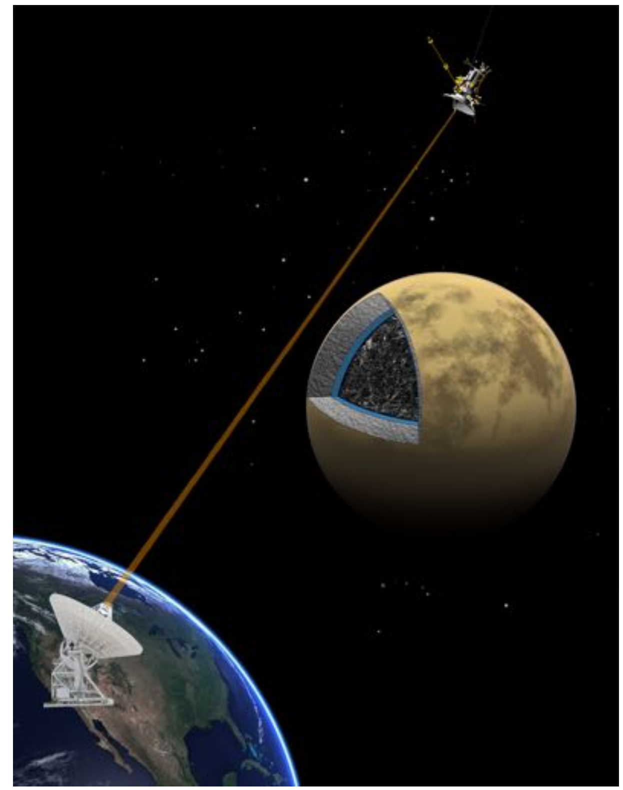
Radio Science

A Key Tool for Solar System Exploration
Producing Many Important Discoveries

Utilize the telecommunication links between spacecraft and Earth to examine changes in phase/frequency, amplitude, and polarization of radio signals to investigate:

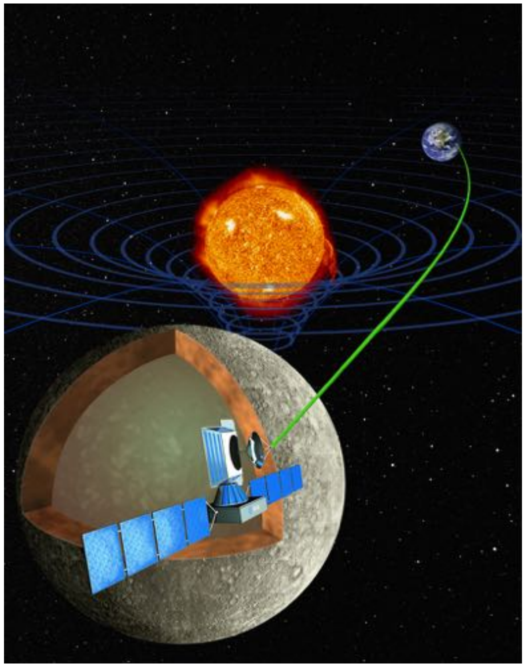
- Planetary atmospheres
- Planetary rings
- Planetary surfaces
- Planetary interiors
- Solar corona and wind
- Comet mass flux
- Fundamental Physics



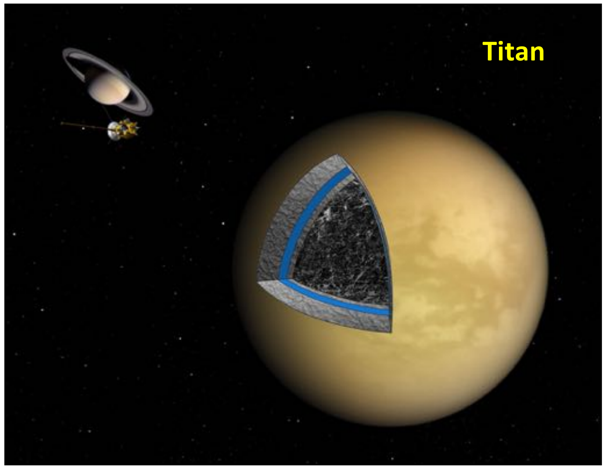


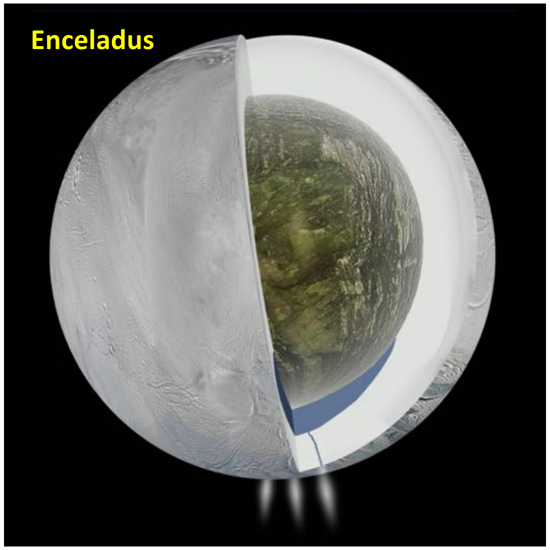
Radio Science Investigation

- **Atmospheres affect the propagation of communication links**
  - *Study solar system atmospheric properties*
- **Gravitational fields alter Doppler shifts due to spacecraft motion**
  - *Study interior structures*
- **Atmospheric motions affect Doppler shifts/phase of situ probes**
  - *Study wind dynamics and turbulence*
- **Small ice and rock particles affect radio phase and amplitude**
  - *Study planetary rings*
- **Surfaces of solar system bodies scatter radio signals**
  - *Study surface material/roughness and near subsurface*
- **Sun’s extended atmosphere alters signal propagation**
  - *Study solar corona and wind*
- **Sun’s gravitational field affects Doppler and range data**
  - *Study fundamental physics*

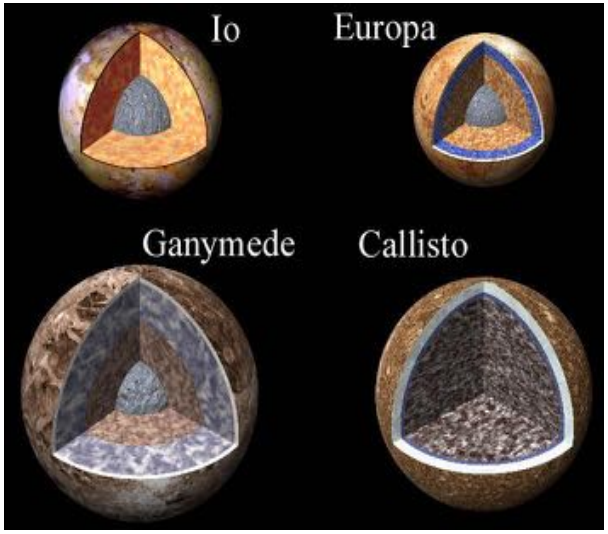


Examples of Gravity Science Results





Models of the interiors of Galilean satellites based on magnetic and gravity measurements



Tidal observations by Cassini gravity team

Titan: Iess et al., 2011 & 2012

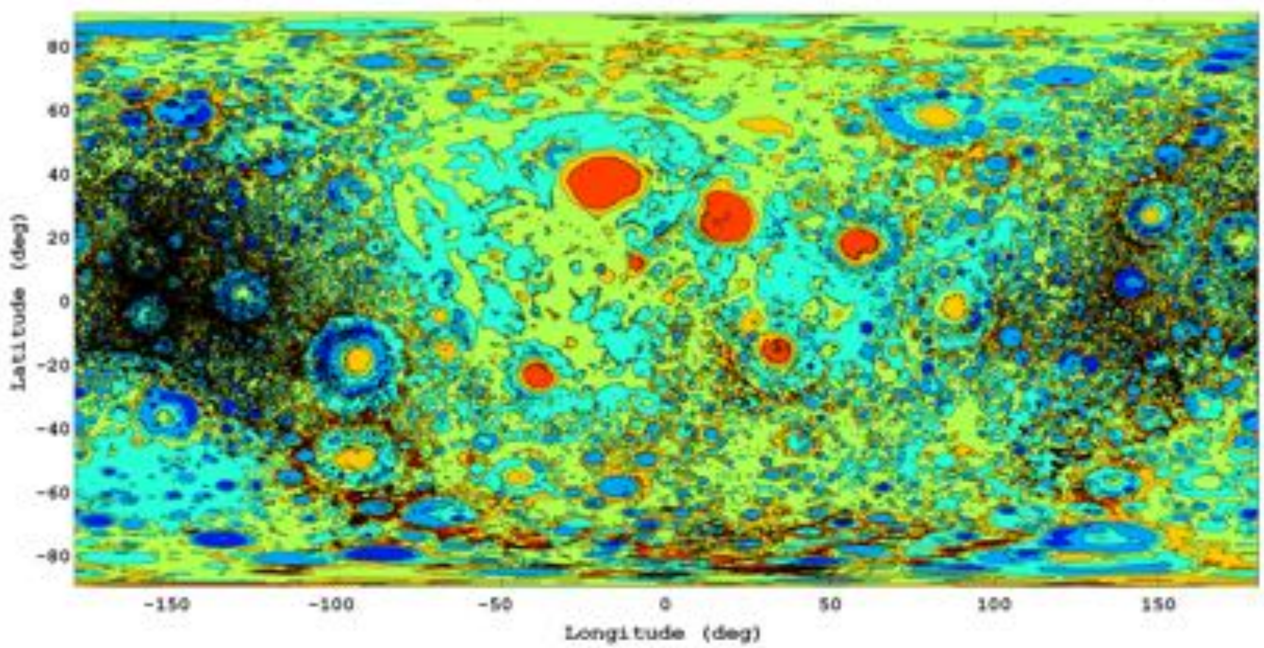
Enceladus: Iess et al., 2014

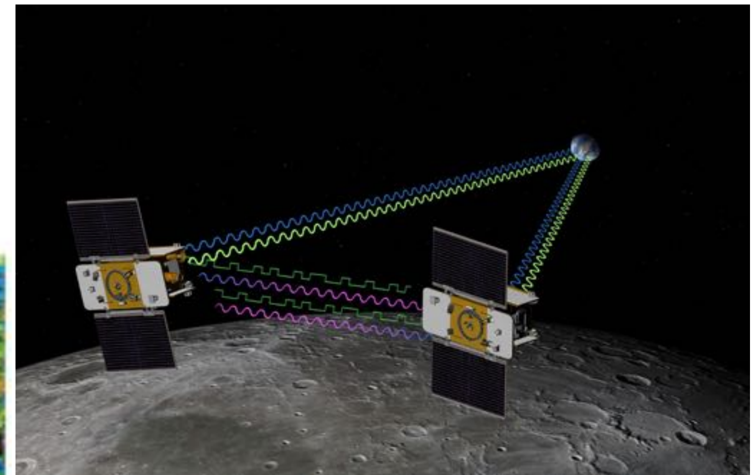
Icy Moons of Large Planets

GRAIL Reveals Lunar Interior Structure

Concept of spacecraft-to-spacecraft crosslinks

GRACE Earth mission
GRAIL at the Moon

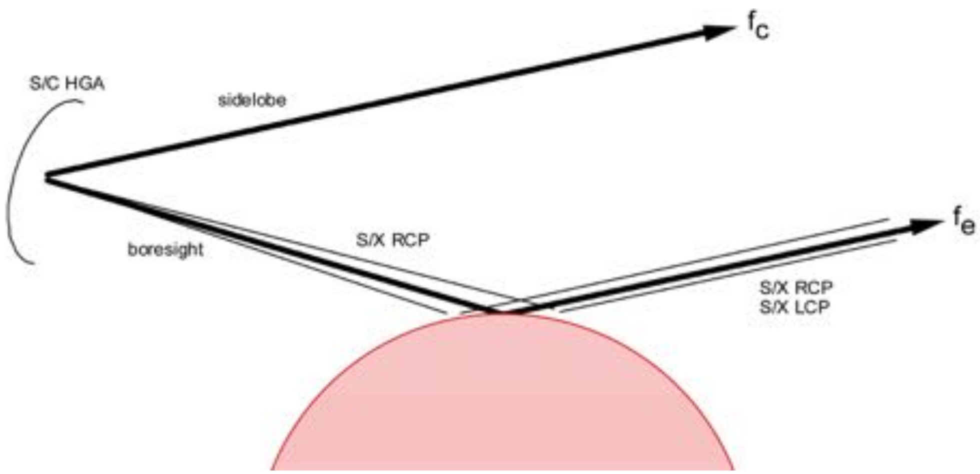


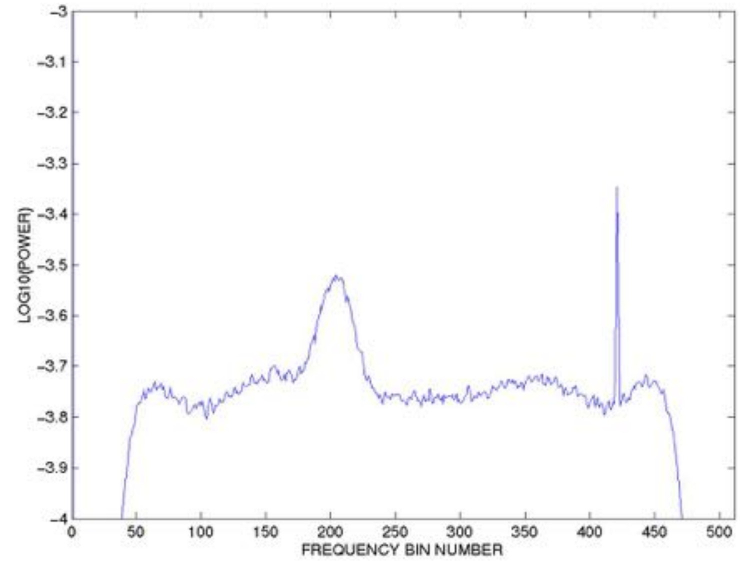


Other Investigation Concepts in Planetary Radio Science

Surface Properties from Signal Scattering

"Bistatic Radar"





- **Study properties of planetary surfaces**
  - **Roughness & dielectric constant**
- **Observables:**
  - **Ratio of received energy in same and opposite polarizations**

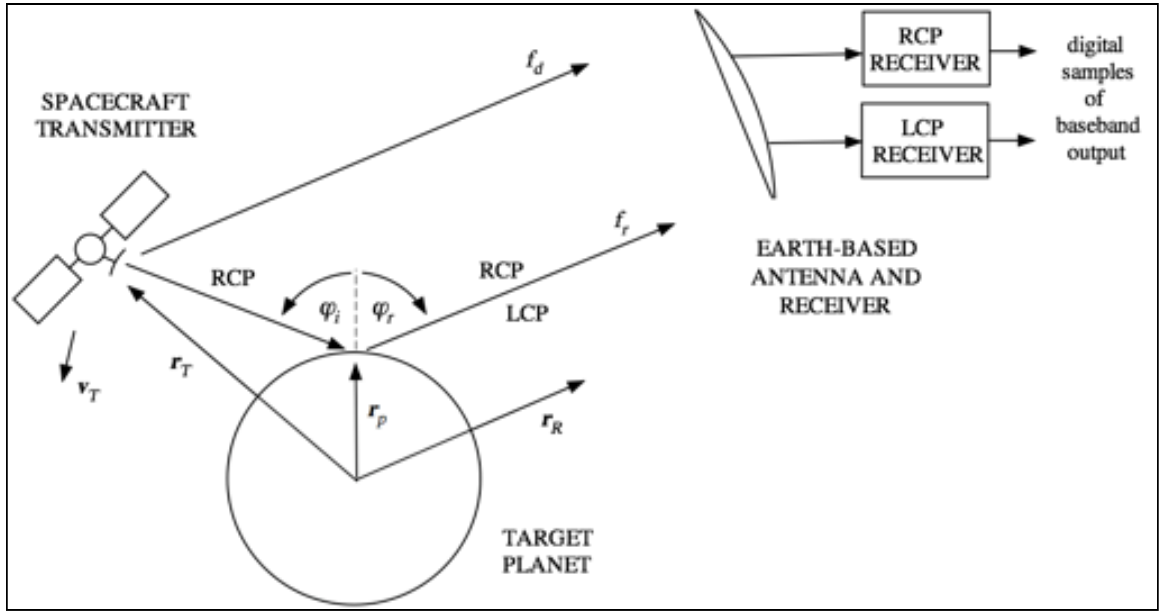
Graphics Credit: R. Simpson

Bistatic Radar Configurations

- Echo Doppler offset = $f_r - f_d$
- Potentially sensitive to topography

- Spacecraft antenna illuminates region
- Local wavelength-scale roughness disperses echo
- Infer roughness from dispersion

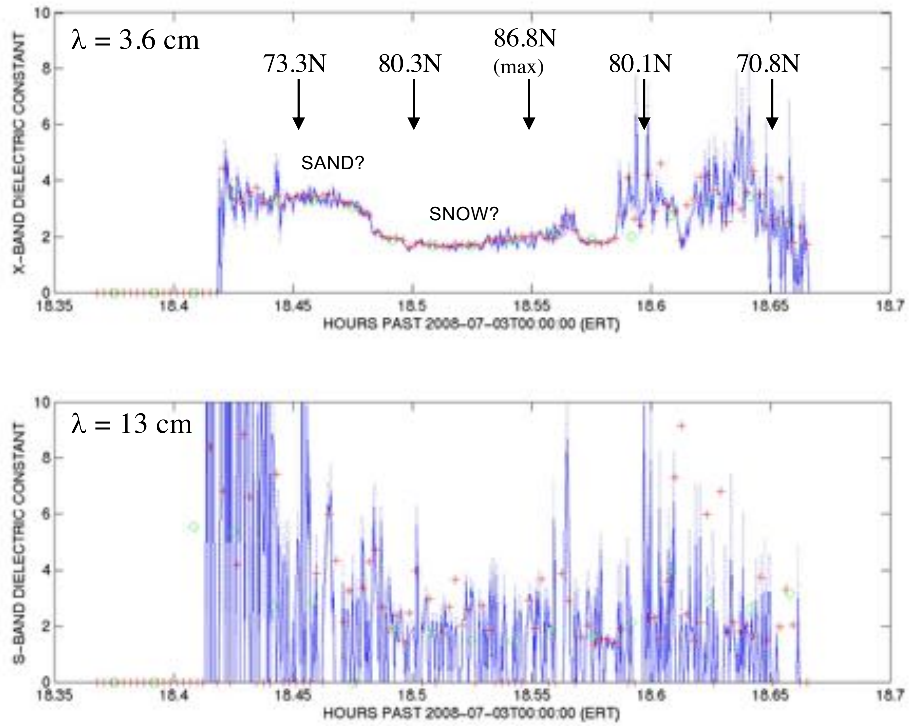
- Forward Scatter =
  Specular Reflection
- Echo Power → Dielectric Constant
- Dielectric Constant →
  Surface Density
- Polarization Confirms



- Spacecraft antenna pointing follows specular point
- Dual polarization receiving
- Multiple frequencies (option)

Graphics Credit: R. Simpson

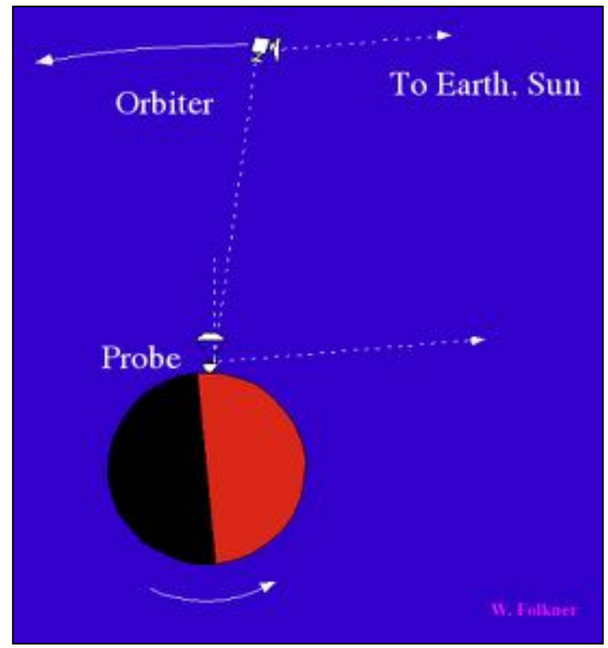
Mars Express Bistatic Radar 2008/185
Dielectric Constant ε from RCP/LCP Power Ratio



Graphics Credit: R. Simpson

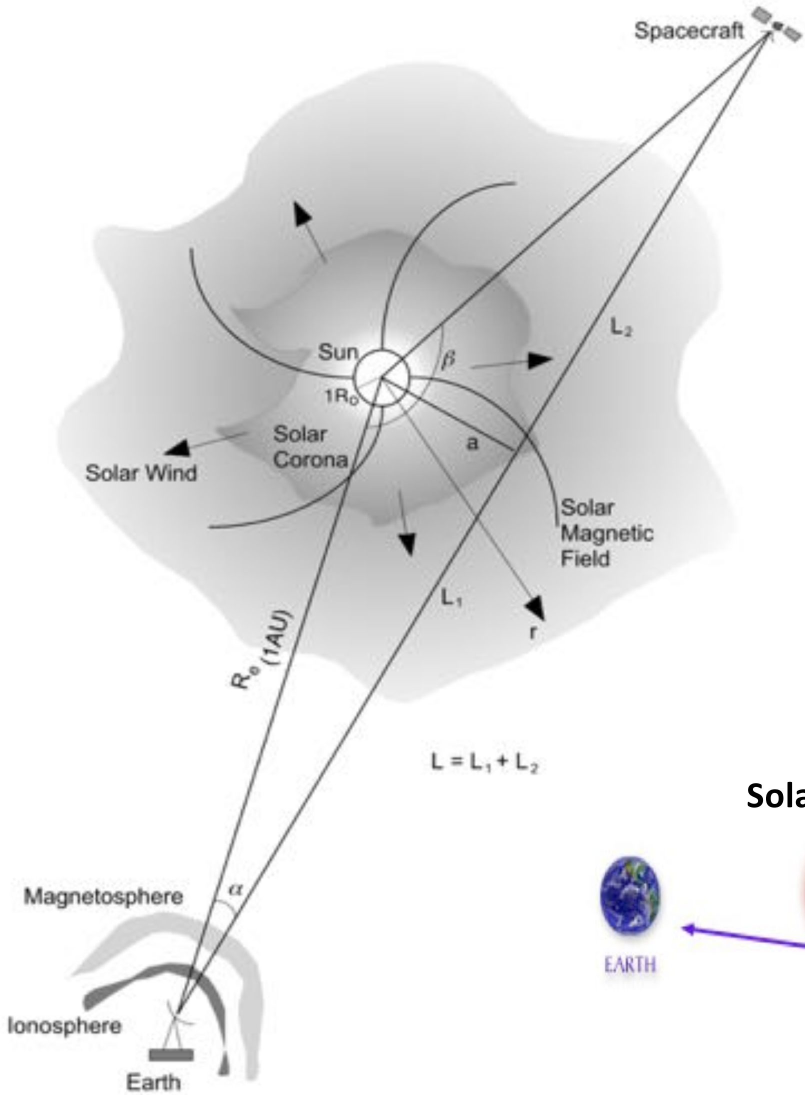
Other Investigation Concepts in Planetary Radio Science

Wind Dynamics from Doppler

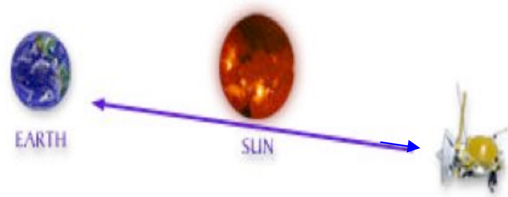


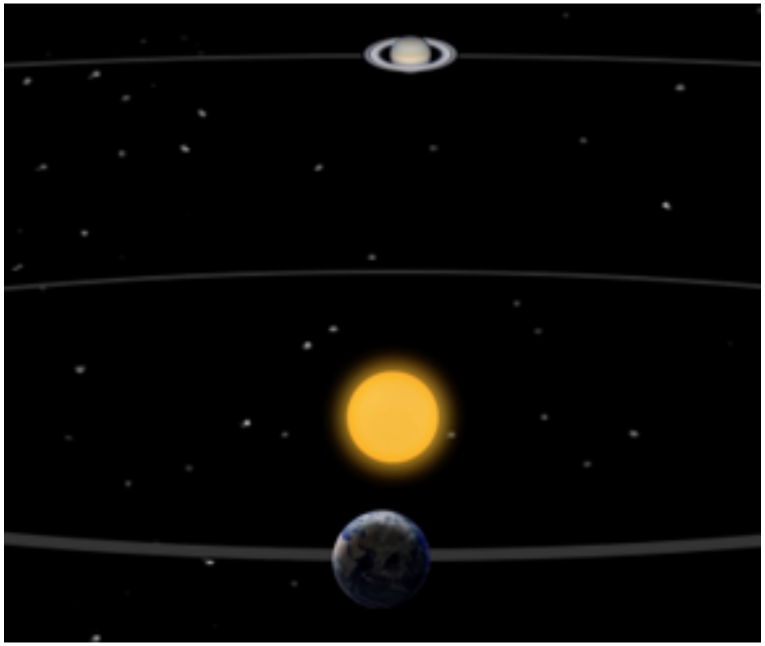
Other Investigation Concepts in Planetary Radio Science

Occultation by atmosphere of the Sun



Solar Conjunction





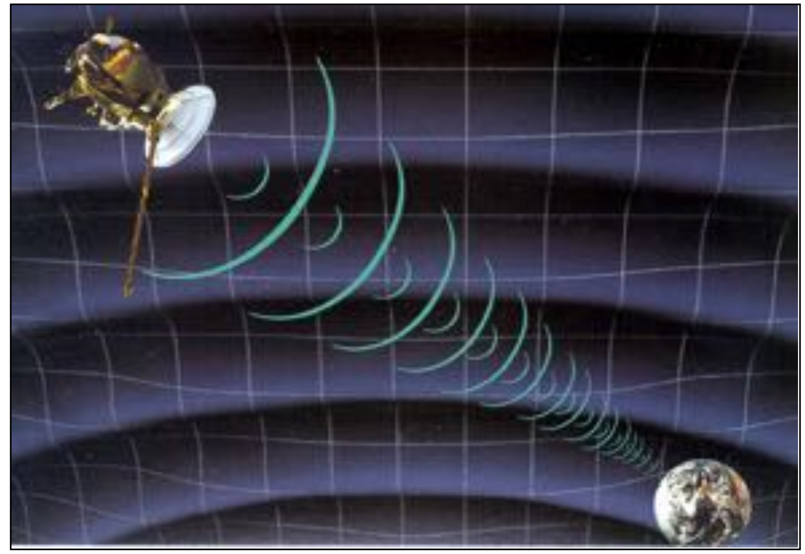
Relativistic Time Delay

- Determine Post-Newtonian Parameters
  - Bending due to Sun's gravitational potential
  - Formulated in General Theory of Relativity
  - Parameter describes curvature of space-time
- Observe time delay from frequency shift
- Cassini Solar Conjunction experiment in 2002
  - Gamma = $1+(2.1\pm2.3)\times10^{-5}$
- Multiple links to calibrate interplanetary plasma
- Water vapor radiometer to calibrate troposphere
- Precise antenna pointing
- Open-loop and tracking receivers
- Quiet Spacecraft: reaction wheels

Bertotti et al. 2003
Source: nature.com
For illustration purposes only

Search for Gravitation Waves

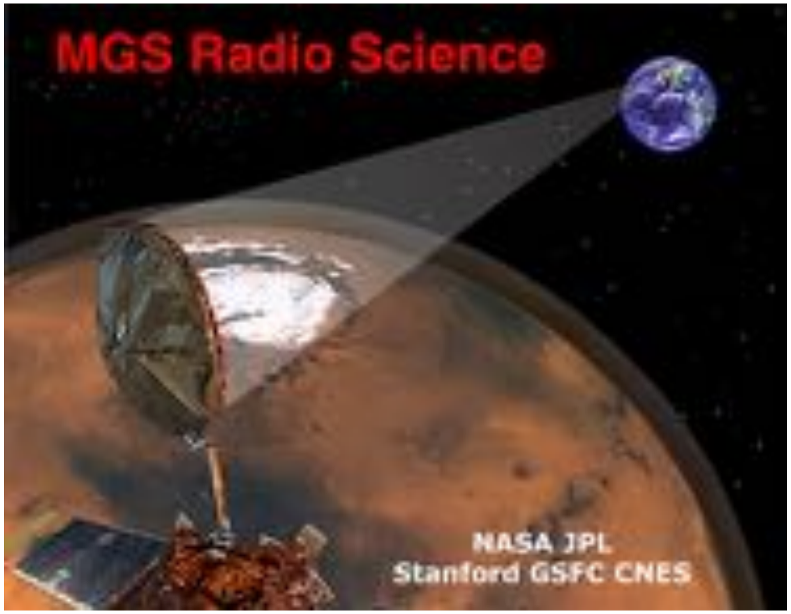
- Search for gravitational waves crossing solar system
  - Propagating, polarized gravitational field
    - Predicted by all relativistic theories of gravity
    - Changes distance between separated test masses
    - Extremely weak—only detectable from astrophysical sources
  - Low frequency (long period) waves
    - Doppler method sensitive in millihertz range
- Observables:
  - Relative distance between spacecraft and station
    - Typically 40 days and 40 nights during solar oppositions



Solar Opposition

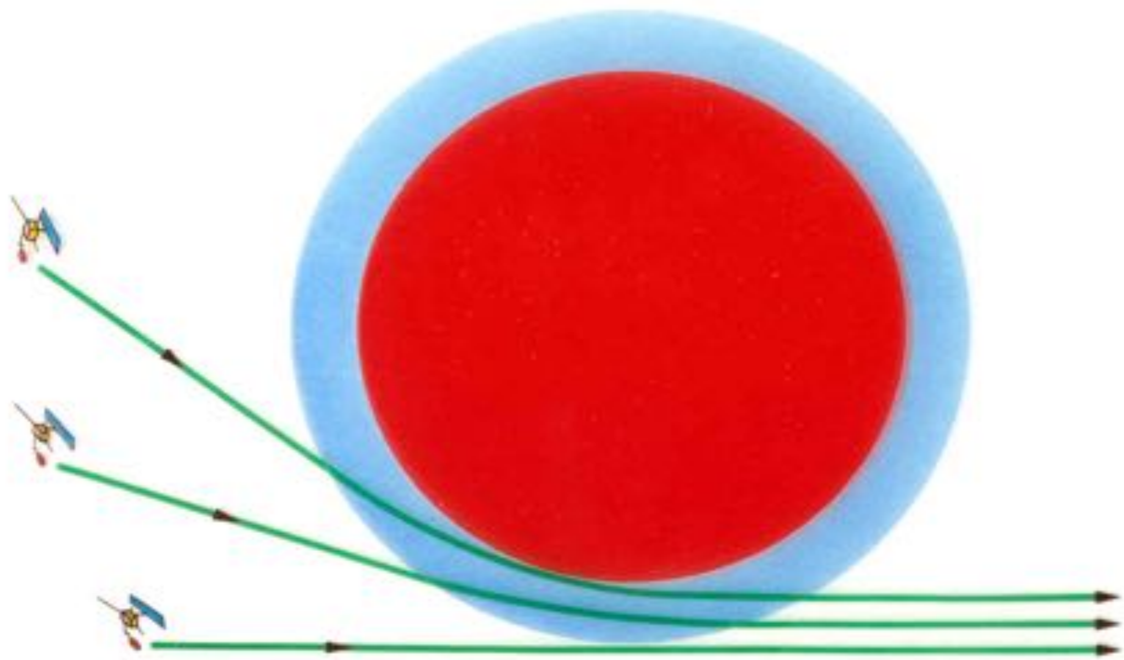
More Details on . . .

Atmospheric Profiles from RS Radio Occultations



Radio Atmospheric Occultation Methodology

Phase ==> length ==> refractive angle ==> refractivity ==> number density ==>column pressure ==> temperature



Graphics Credit: M. Patzold

Radio Atmospheric Occultation Formulations

Two frequencies are needed to separate dispersive (plasma) from non-dispersive effects (orbit, neutral atmosphere, systemic errors, …)

Refraction index of plasma

$$n = 1 - \frac{40.3\left(m^3 s^{-2}\right) N_e}{f^2}$$

Group/phase change

$$T_{gr/ph} = \int \frac{ds}{v_{gr/ph}} = \frac{s}{c} \pm \frac{40.3}{c f^2} \int_0^s N_e \, ds$$

Received phase

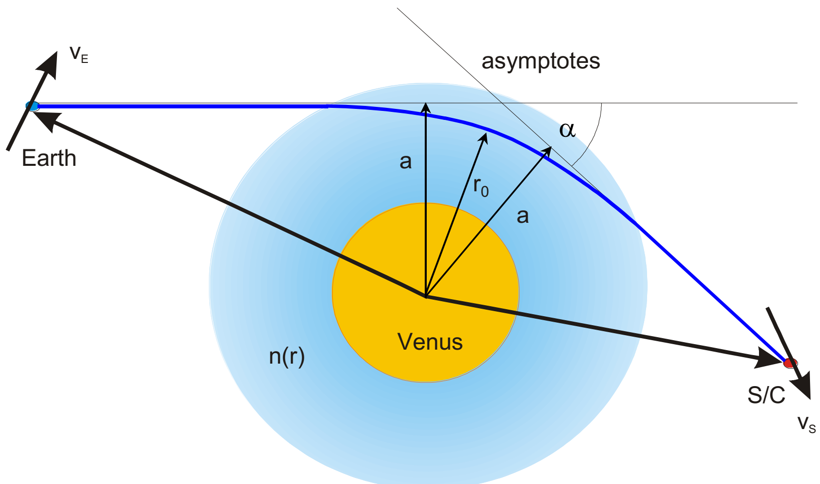
$$\theta_R(t) = 2\pi f_T \left[t - \frac{s(t)}{c} + \frac{40.3}{c f_T^2} I(t) \right]$$

Measured frequency at ground station

$$f_R(t) = \frac{1}{2\pi} \frac{d\theta_R}{dt} = f_T \left[1 - \frac{\dot{s}}{c} + \frac{40.3}{c f_T^2} \dot{I}(t) \right]$$

Straight Line Doppler Effect

Compare to effect without atmosphere to derive frequency Residuals



$$\phi = -\sum_i \frac{G \cdot M_i}{r_i}$$

$$\beta_{S,E} = \mathrm{v}_{S,E} / \mathrm{c}$$

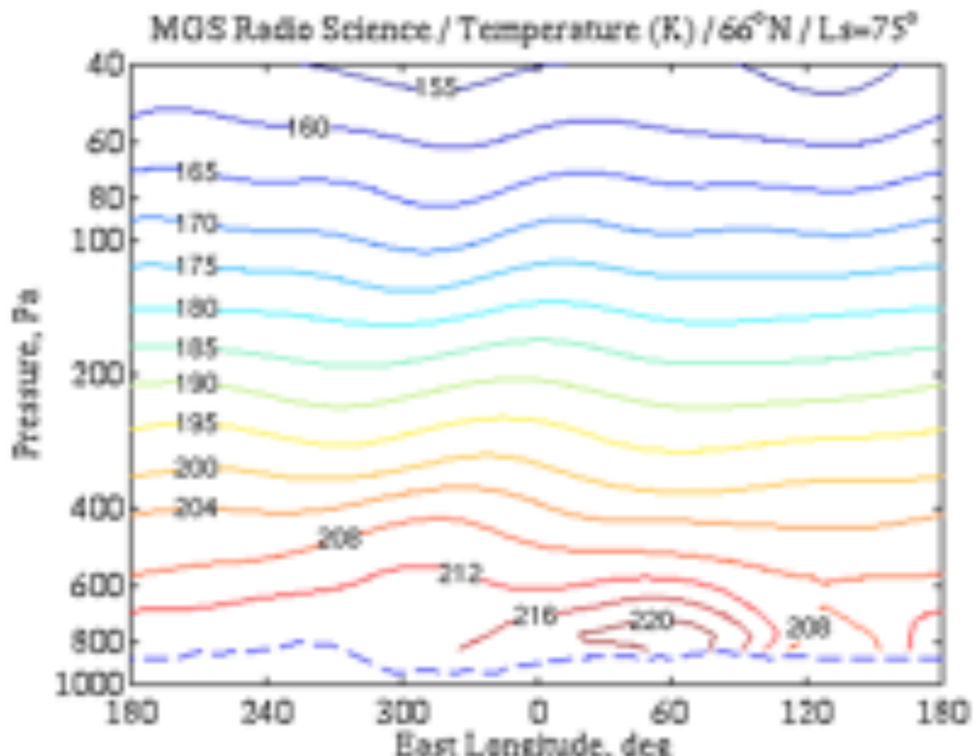
$$\Delta f_0 = f_S - f_E = f_S \left\{ \hat{\mathbf{n}} \cdot \left(\boldsymbol{\beta}_E - \boldsymbol{\beta}_S \right) + \frac{1}{2} \left(\beta_S^2 - \beta_E^2 \right) + \left(\hat{\mathbf{n}} \cdot \boldsymbol{\beta}_S \right) \left(\hat{\mathbf{n}} \cdot \boldsymbol{\beta}_E \right) - \left(\hat{\mathbf{n}} \cdot \boldsymbol{\beta}_S \right)^2 - \frac{1}{c^2} \left(\varphi_S - \varphi_E \right) \right\}$$

Valid in an inertial (barycentric) system

Radio Occultations (RO)

- **Study properties of planetary media along propagation path**
  - **Atmosphere: temperature-pressure profile**
  - **Ionosphere: electron density**
  - **Rings: particle structure and size distribution**
  - **Byproducts: planetary shapes**
- **Observables:**
  - **Amplitude and phase**
    - **Refraction**
    - **Scattering**
    - **Edge diffraction**
    - **Multi-path**

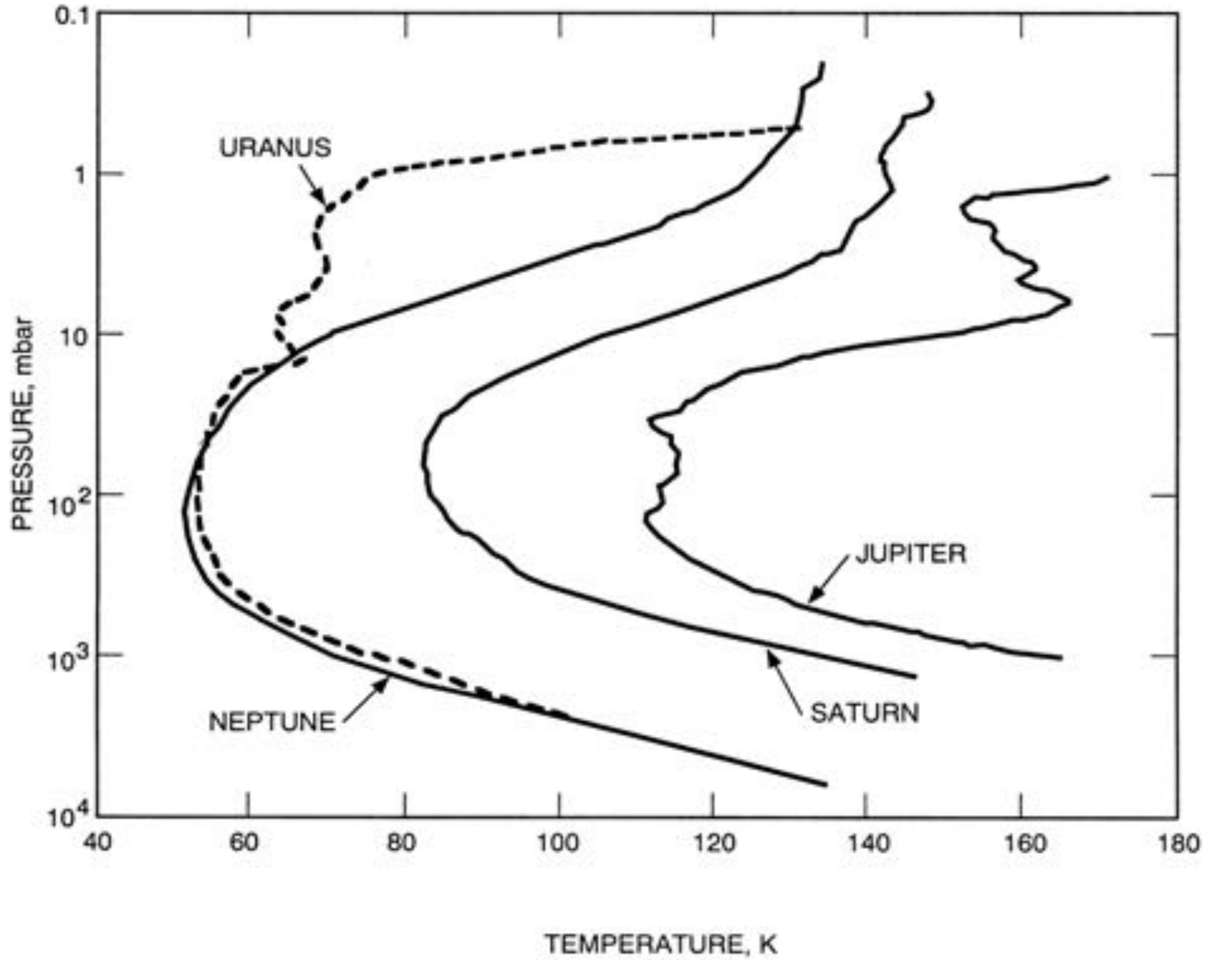
Atmosphere of Mars from MGS Occultations



Source: D. Hinson

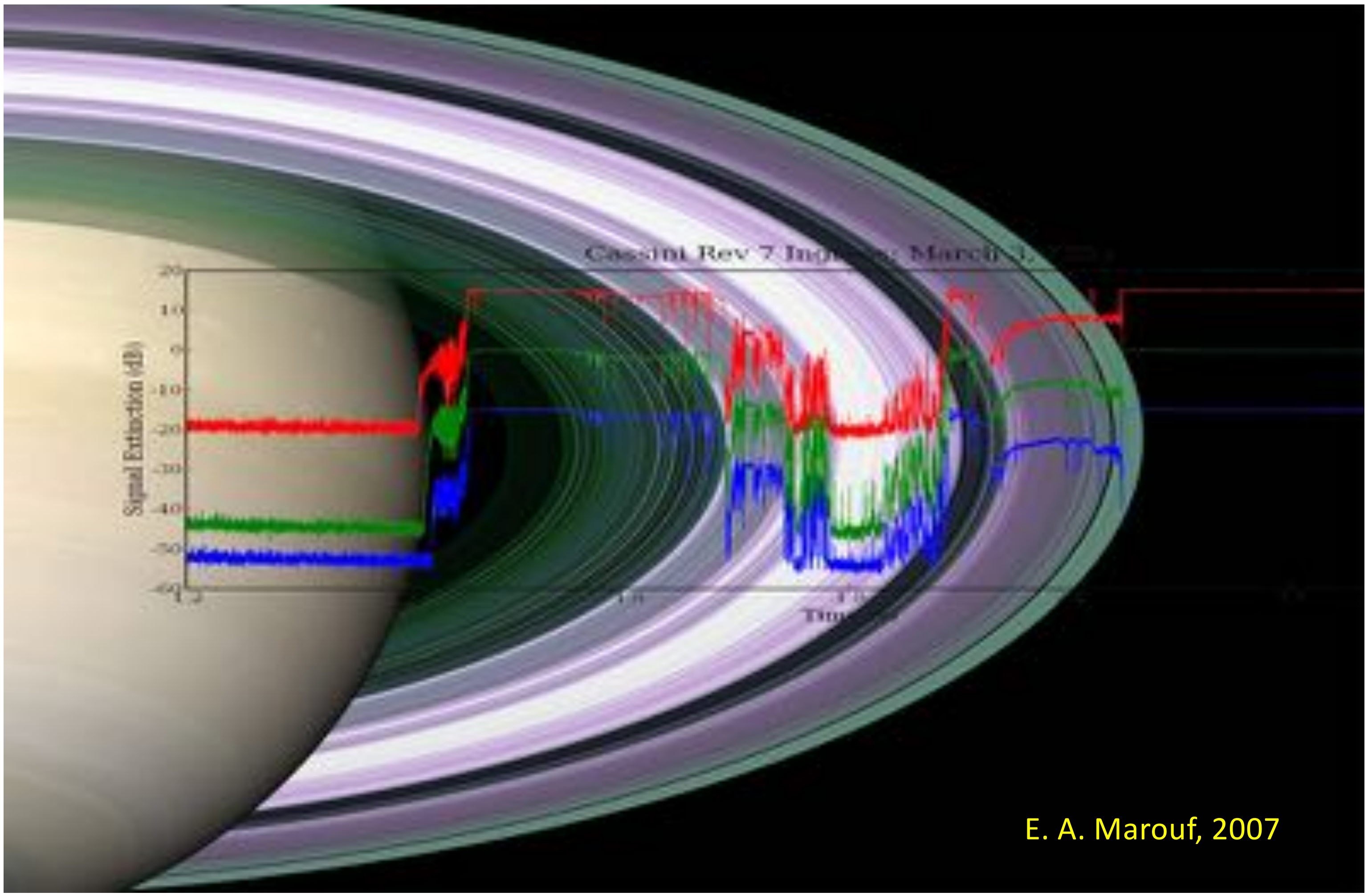
Atmospheres of Giant Planets

Occultations of Voyager 2 by outer planets



Temperature profiles for the giant planets derived from radio occultation data acquired with the Voyager spacecraft (from Lindal, 1992)

Saturn’s Rings In the Cassini Era

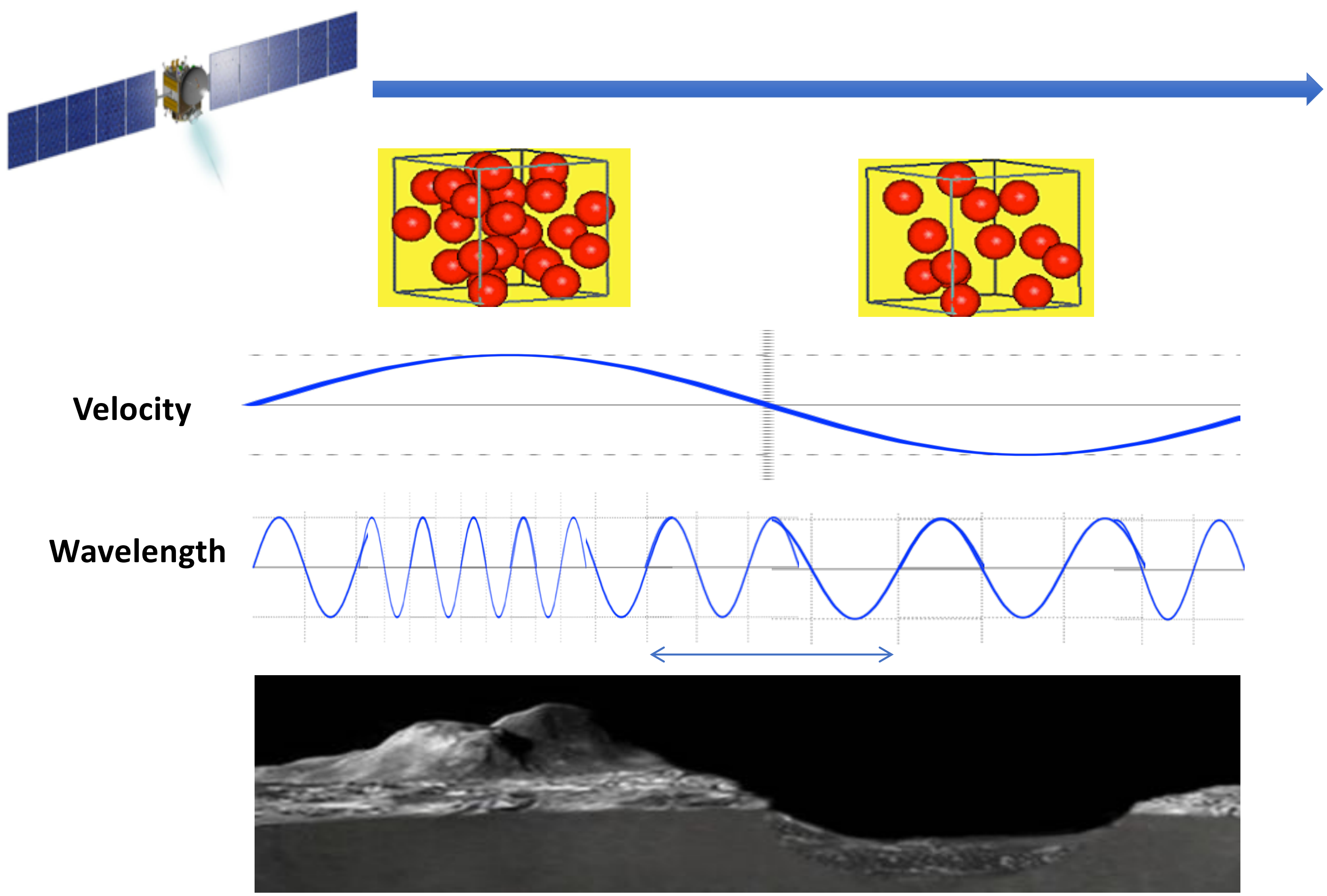


More Details on . . .

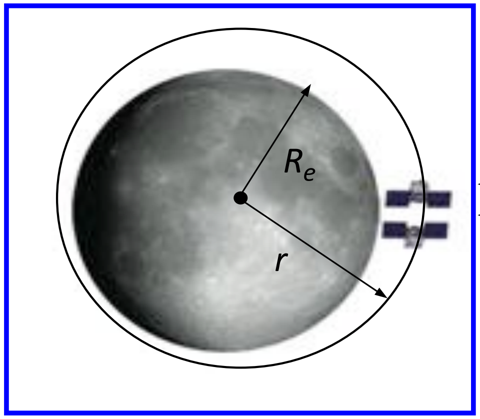
Gravitational Fields from Precision Doppler Measurements

How to Observe Gravity

- Box on left has more material than box on right
- It has higher density = mass / volume
- Gravity is an attractive force that is proportional to the mass inside each box
- Gravity is different where the density is different
- Gravity also depends on distance squared from the center of mass
- Spacecraft speeds up near a dense object and slows down near a less dense one
- Doppler signal from spacecraft to station carries information



Gravity from tracking data



lat: $\emptyset$,
long: λ

Deep Space Network

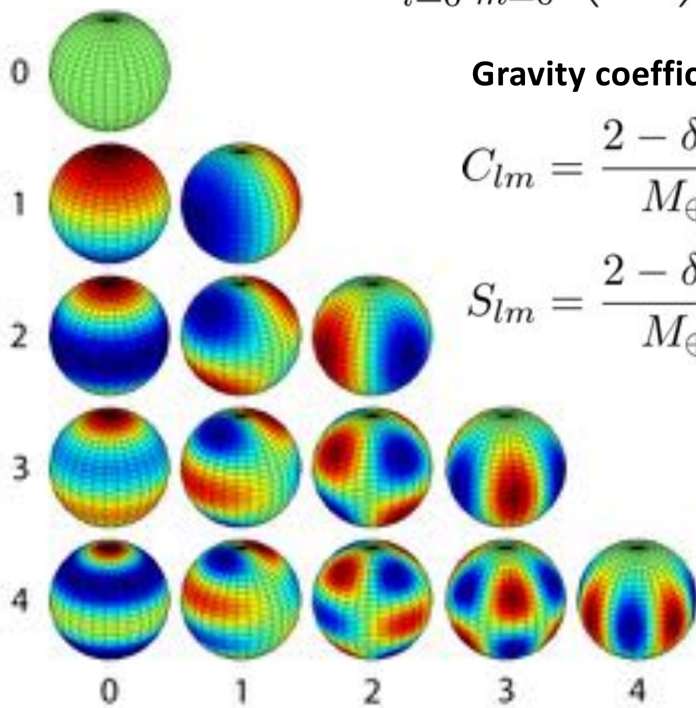
Potential function
Legendre polynomial
Spherical harmonic coefficients

$$U(r,\phi,\lambda) = \frac{GM}{r}\sum_{n=0}^{180}\sum_{m=0}^{n}\left(\frac{R_e}{r}\right)^n \bar{P}_{nm}(\sin\phi)\left[\bar{C}_{nm}\cos(m\lambda) + \bar{S}_{nm}\sin(m\lambda)\right]$$

Another Gravity Field Mathematical Representation

Potential function represented in terms of spherical harmonic expansion

$$V(r,\theta,\varphi)=\frac{GM_{\oplus}}{r}\sum_{l=0}^{\infty}\sum_{m=0}^{l}\left(\frac{R_{\oplus}^{l}}{r^{l}}\right)P_{lm}\left(\sin\theta\right)\left(C_{lm}\cos\left(m\varphi\right)+S_{lm}\sin\left(m\varphi\right)\right)$$



Gravity coefficients

$$C_{lm}=\frac{2-\delta_{0m}}{M_{\oplus}}\frac{(l-m)!}{(l+m)!}\int\frac{s^{l}}{R_{\oplus}^{l}}P_{lm}\left(\sin\theta\right)\cos\left(m\varphi\right)\rho(\boldsymbol{s})\mathrm{d}V$$

$$S_{lm}=\frac{2-\delta_{0m}}{M_{\oplus}}\frac{(l-m)!}{(l+m)!}\int\frac{s^{l}}{R_{\oplus}^{l}}P_{lm}\left(\sin\theta\right)\sin\left(m\varphi\right)\rho(\boldsymbol{s})\mathrm{d}V$$

Legendre Polynomials

$$P_{lm}(u)=\left(1-u^{2}\right)^{\frac{m}{2}}\frac{d^{m}}{du^{m}}P_{l}(u)$$

$$P_{l}(u)=\frac{1}{2^{l}l!}\frac{d^{l}}{du^{l}}\left(u^{2}-1\right)^{l}$$

Planetary Gravity

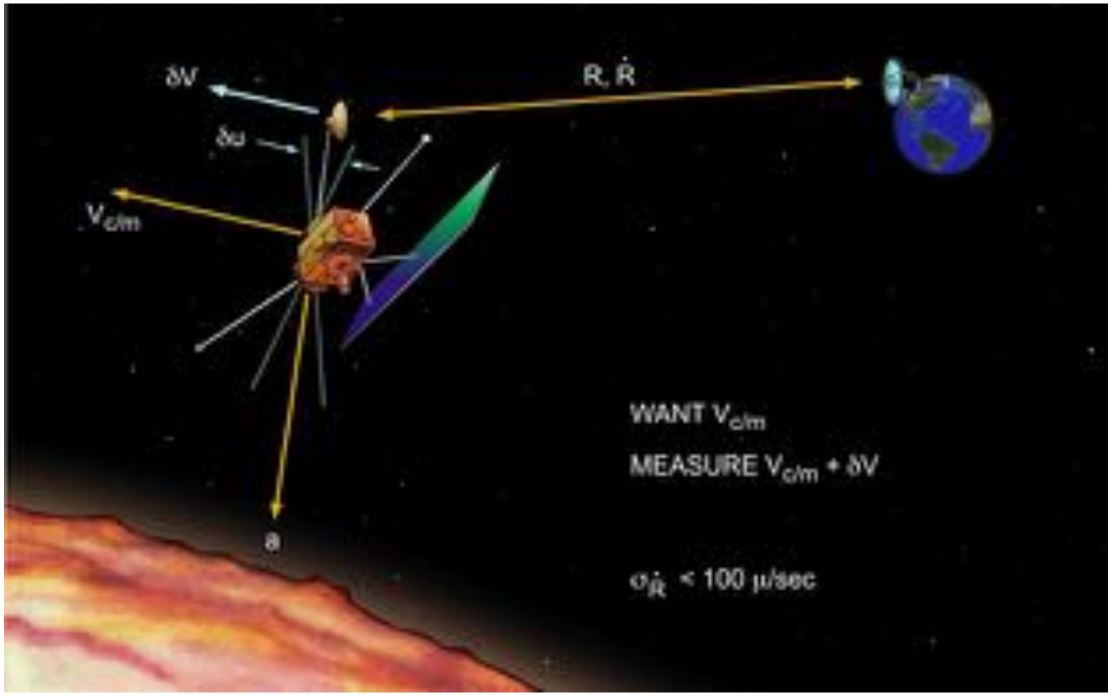
- Jupiter has much more mass than Earth & much more gravity
  - But a lot less density
- At its equator, Jupiter's surface gravity is only 2.5 times Earth's surface gravity because Jupiter is so big
- Dependence on total mass inside the body and the distribution of mass

Jupiter:
Diameter: 139822 km (~ 11 x Earth)
Mass: 1.8986×10^{27} kg (~ 317 x Earth)
Average Density: 1326 kg/m^3
Surface Gravity: ~ 2.4 g (~ 23 m/s^2)

Earth:
Diameter: 12742 km
Mass: 5.97219×10^{24} kg
Average Density: 5515 kg/m^3 (~ 4.2 x Jupiter)
Surface Gravity: 1 g (9.8 m/s^2)

Doppler Observable

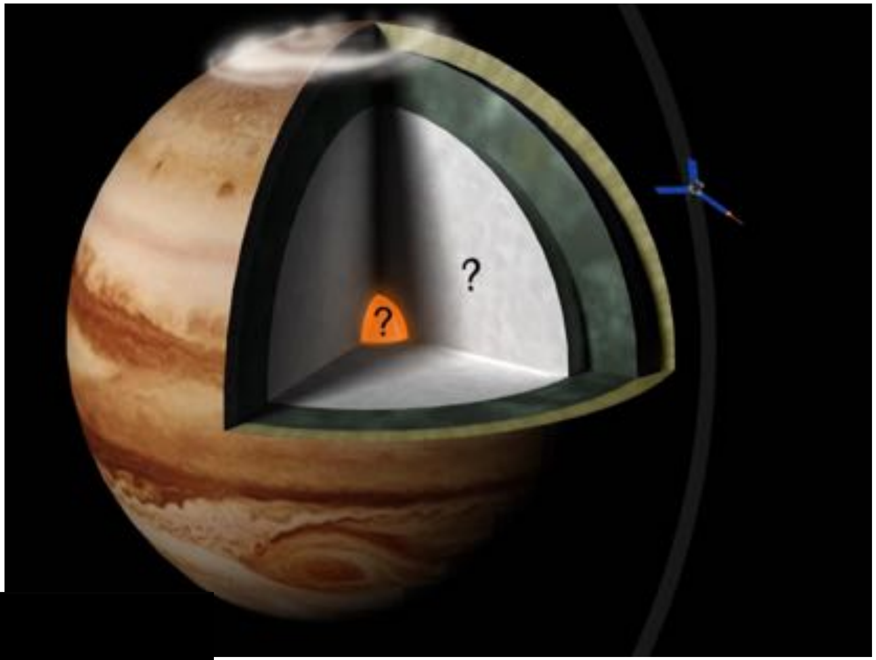
- Determine the mass and mass distribution
  - GM of body or system (planet + satellites)
  - Gravity field: higher order expansion of mass distribution
- Constrain models of internal structure
  - Examples: ocean on Europa
- Improve orbits and ephemerides
- Observables:
  - Doppler and range: precise measurement of relative motion
    - Doppler accuracy ~ 0.03 mm/s at X, few microns/s at Ka-band
    - Ranging accuracy to ~ 1 meter

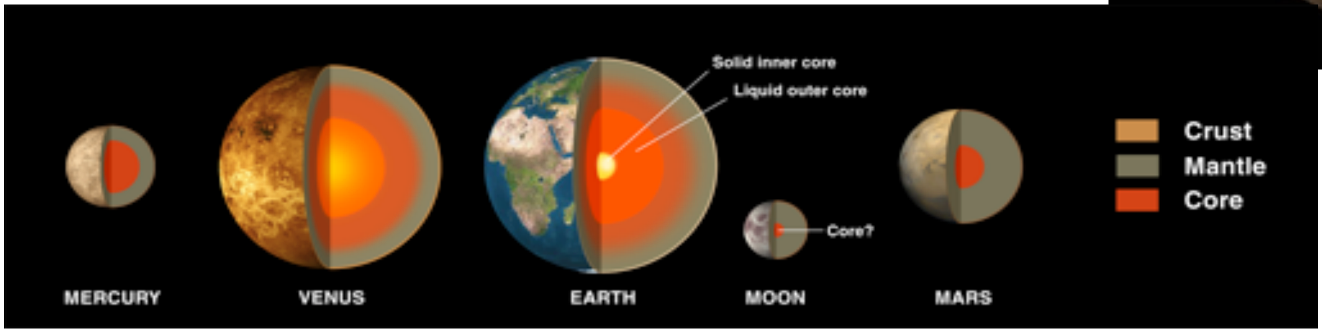


Juno Revealing Jupiter's Interior Structure

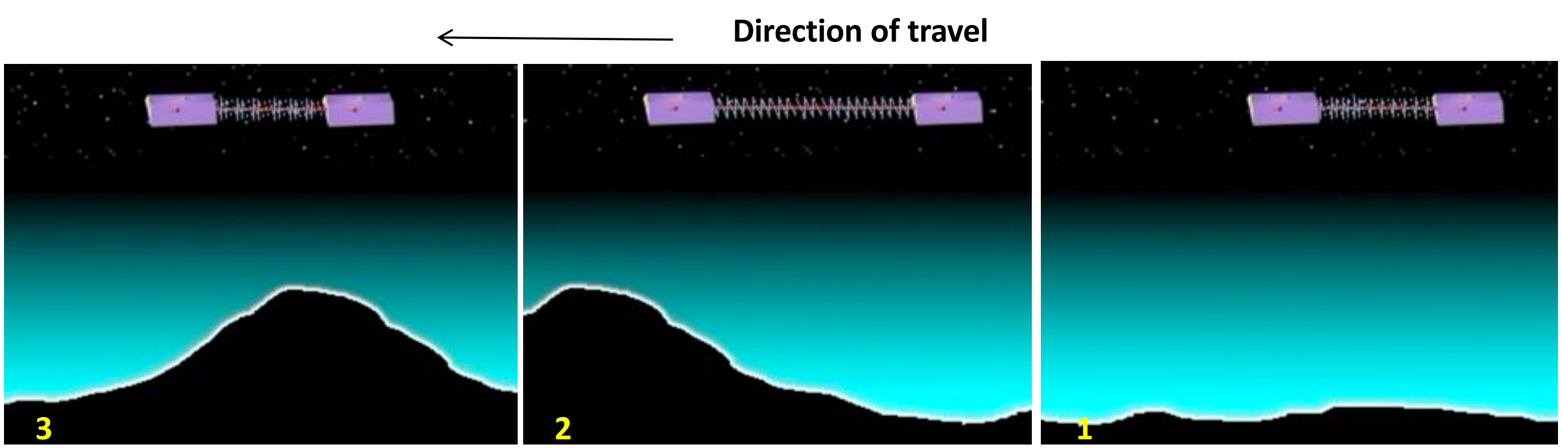
Juno Gravity Science:

- Precise measurement of spacecraft motion measures gravity field
- Close-in Juno polar orbit maximizes sensitivity to gravity
- Distribution of mass reveals core and deep structure
- Higher degree harmonics reveal convective motion in deep atmosphere





GRACE/GRAIL Measurement Concept

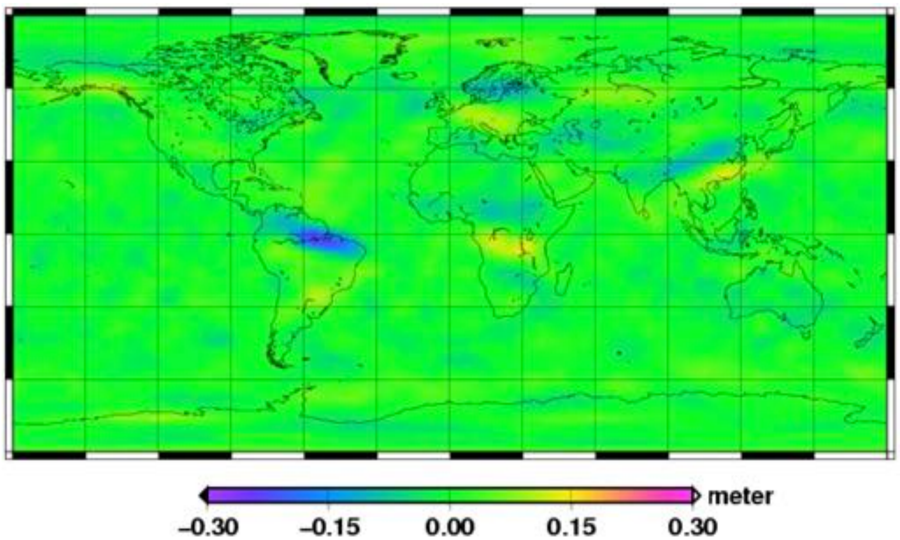


Separation distance between two spacecraft:

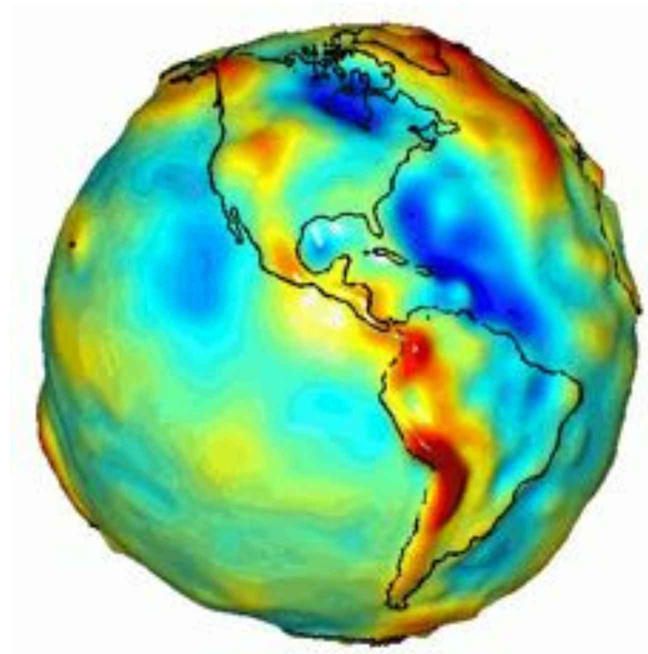
1. Nominal
2. Increases as leading spacecraft senses positive gravity anomaly due to mountain
3. Decreases as trailing spacecraft senses positive gravity anomaly due to mountain

Earth's Gravity Varies with Time

- Earth's gravity varies due to mountains and valleys as well as different density in the materials beneath the surface
- Bumpiness changes monthly due to water movement

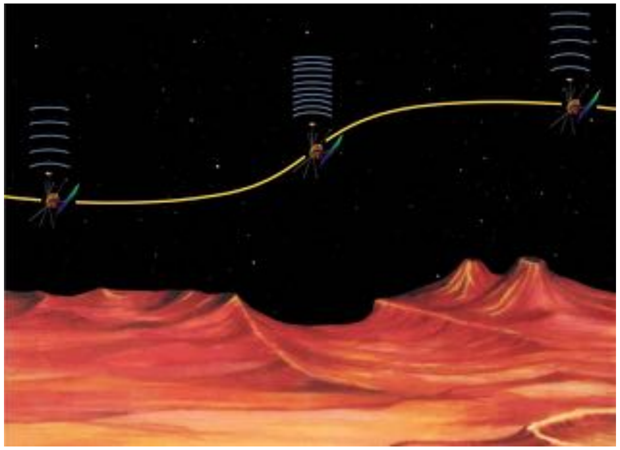


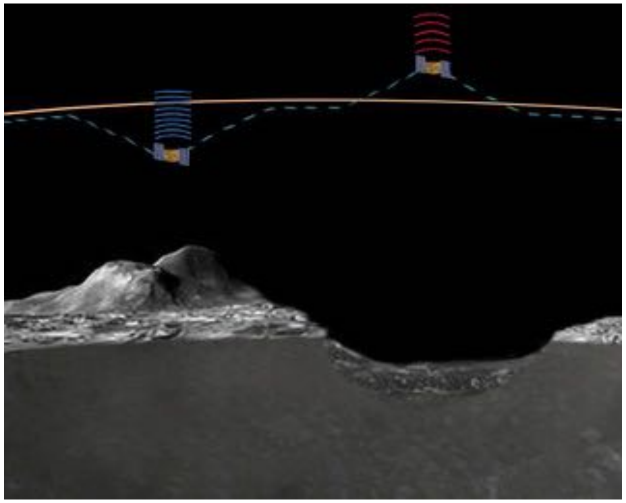
- Monthly surface mass variation in equivalent water height - annual wet & dry seasons
- Strongest signal over Amazon basin

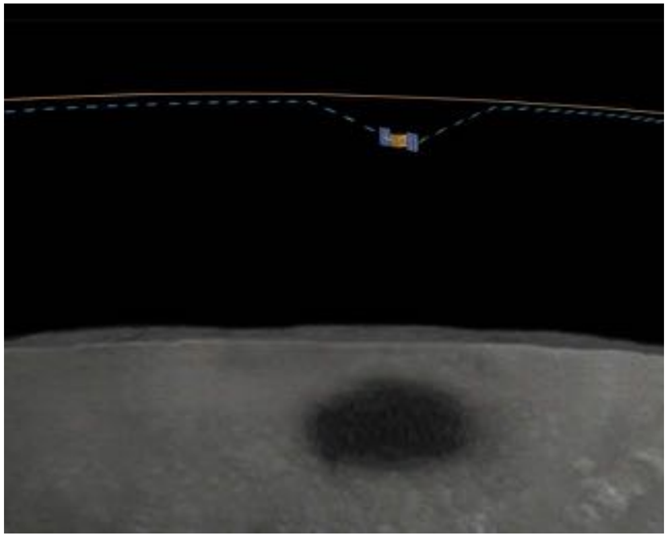


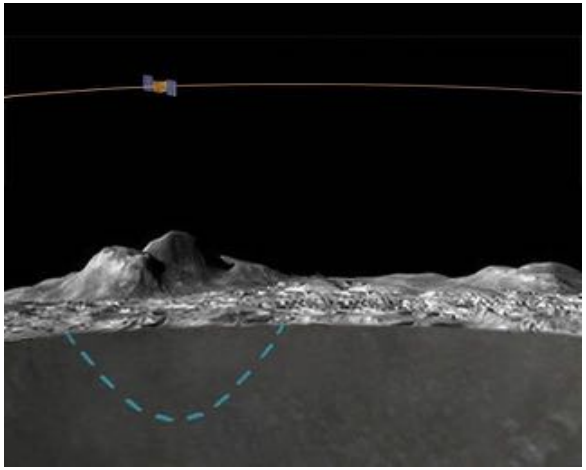
Surface & Sub-Surface Effects

Geophysics at a Glance

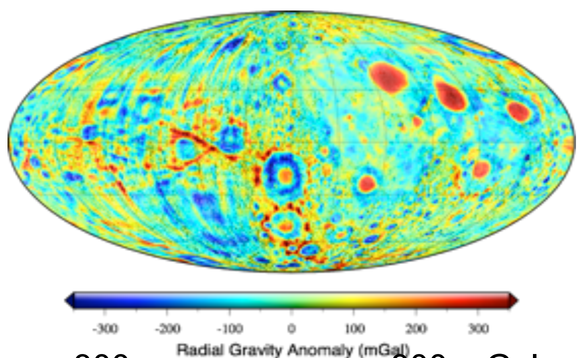








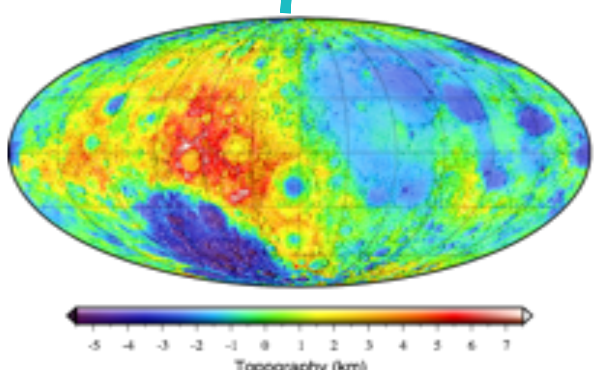
Gravity & Topography (GRAIL Lunar Example)



gravity

-300 +300 mGal

geophysical model



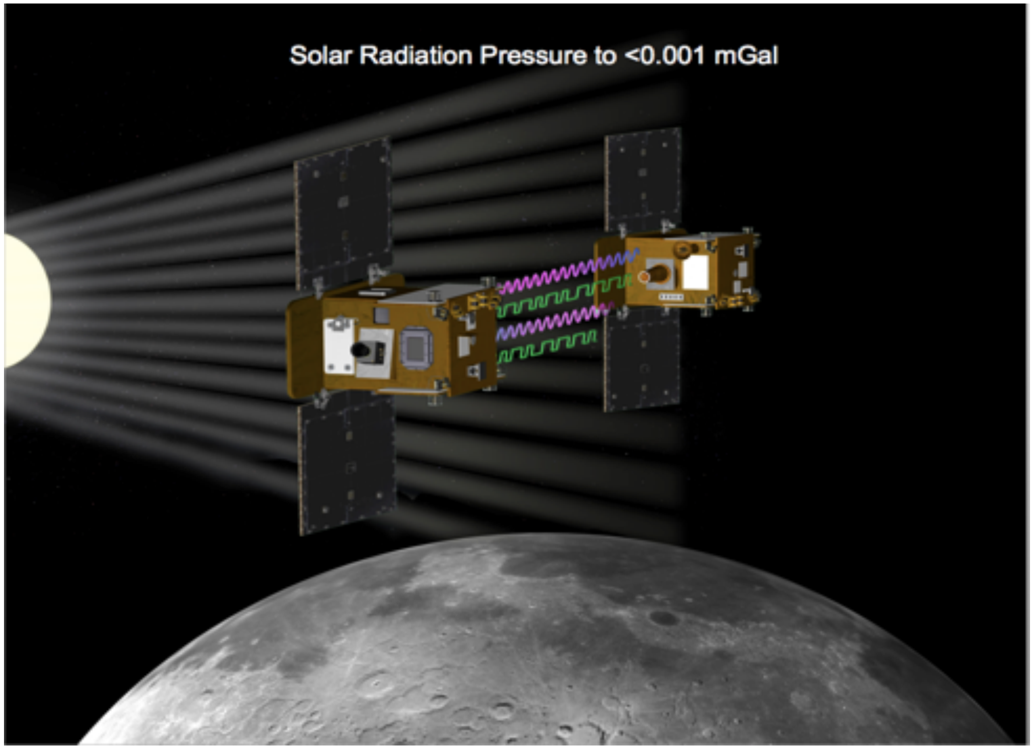
topography

-9 +10 km

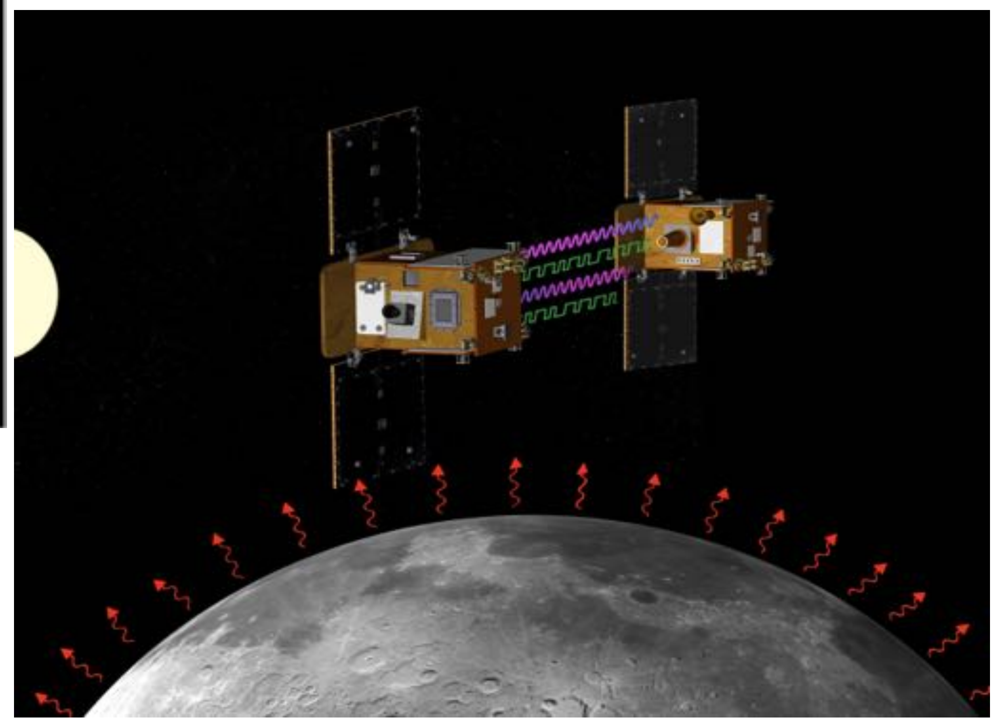
geochemistry
petrology
geology

crustal density
crustal thickness
elastic thickness
load density
surface-subsurface load ratio
phase relationship of loads

internal structure
thermal evolution



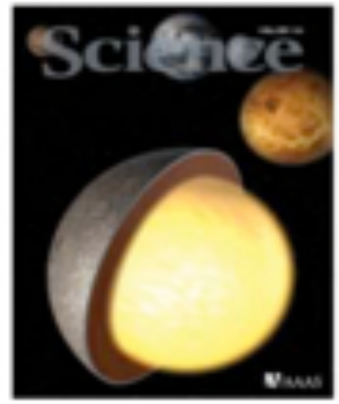
Non-Gravitational Forces



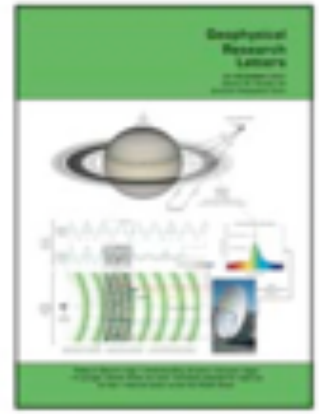
Interior of Ganymede

GRAIL at the Moon

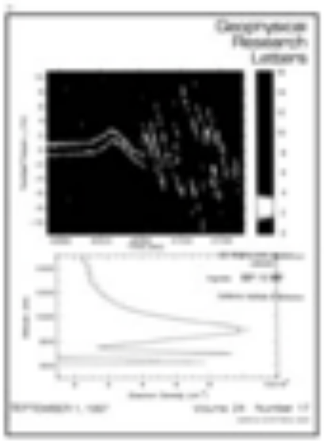
Oceans on Europa?



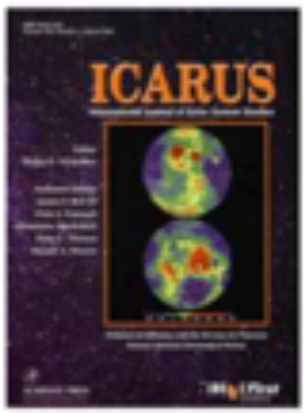
Mercury Liquid Core



Saturn's Rings



Mars Ionosphere



Moon Gravity Field

Rings of Saturn

Crosslink Demo

Special Issue

Sources: nature.com, sciencemag.org, agupubs.onlinelibrary.wiley.com, www.journals.elsevier.com/Icarus, discovermagazine.com, proceedingsoftheieee.ieee.org
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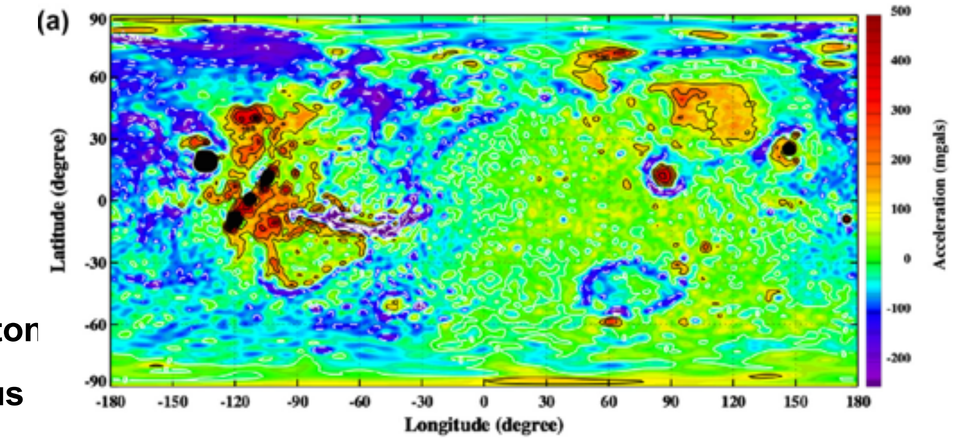
Selected Scientific Accomplishments



Surface gravity anomalies complete to degree and order 90
with respect to a reference ellipsoid (model MRO110B)

Konopliv et al., 2011

- Discovery of lunar mascons
- First estimate of Martian surface pressure
- Structure of Saturn's and Uranus's rings
- Mars atmospheric density from spacecraft drag
- Surface pressure and detection of ionospheres of Titan & Triton
- Electron column density latitude profile of the Io Plasma Torus
- High-resolution gravitational fields of the Moon, Mars, Venus
- First detection of gravity-field variations on a planet (Mars)
- First gravity model of an asteroid
- Measurement of drag deceleration in the comae of comets Halley & Grigg-Skjellerup
- Description of large-scale coronal structure & densities in streamers & holes
- First evidence for acceleration of coronal mass ejections far from Sun
- Profile of deep winds on Jupiter via the Galileo probe and Titan via Huygens
- Surface characteristics of Venus, Moon, Mars via bistatic radar experiments

Cassini Meets Marconi

Uplink Possibilities

X-band ~ 7.9 GHz

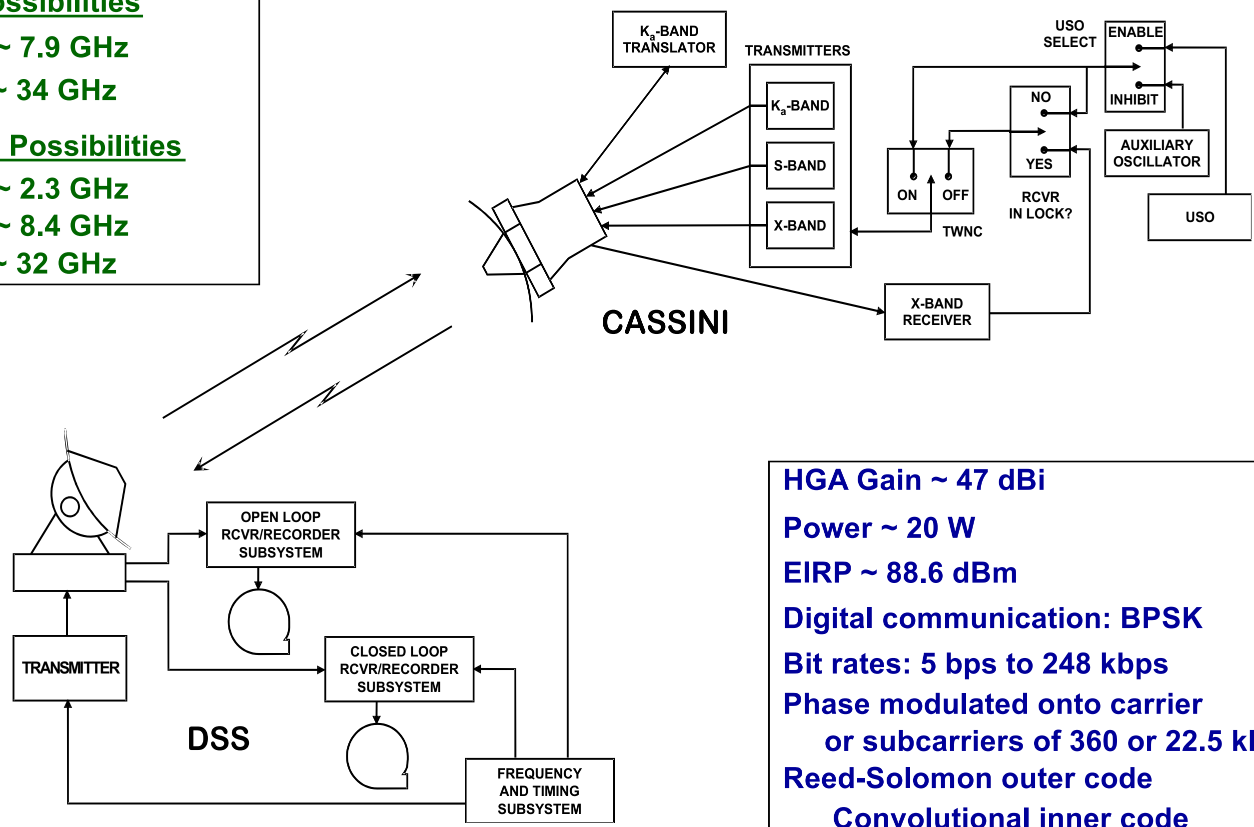
K_a-band ~ 34 GHz

Downlink Possibilities

S-band ~ 2.3 GHz

X-band ~ 8.4 GHz

K_a-band ~ 32 GHz



HGA Gain ~ 47 dBi

Power ~ 20 W

EIRP ~ 88.6 dBm

Digital communication: BPSK

Bit rates: 5 bps to 248 kbps

Phase modulated onto carrier
or subcarriers of 360 or 22.5 kHz

Reed-Solomon outer code
Convolutional inner code

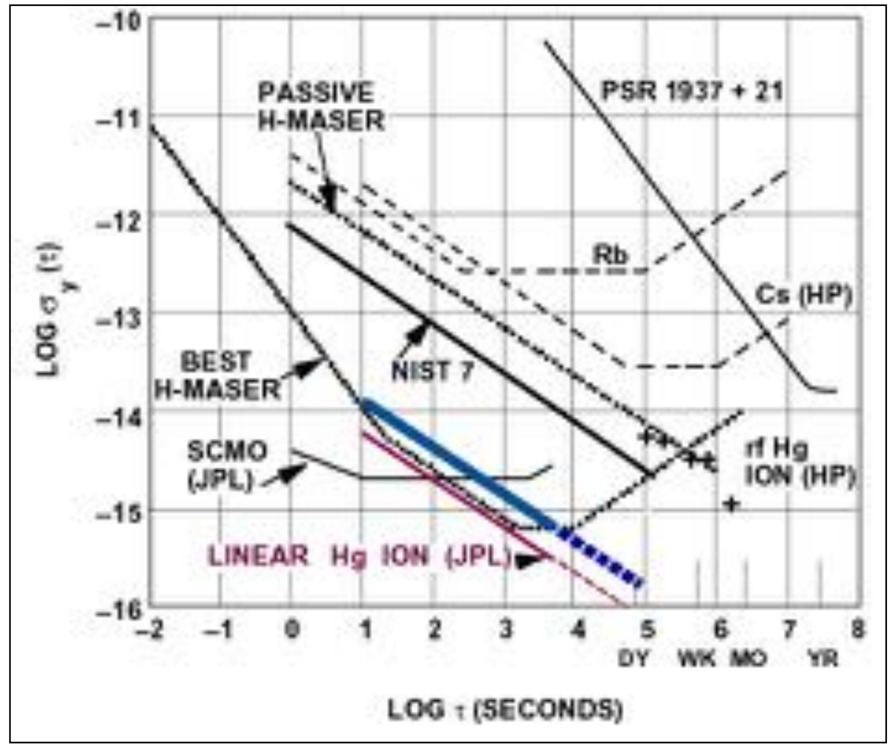
DSN's Open-Loop Receiver (OLR)

The Radio Science Receiver (RSR)

- **Tuned by prediction file generated from navigation information**
- **Remotely operated from JPL**
- **Advantages**
  - **Better stability**
  - **Capture signal dynamics**
  - **Capture multi-path**
  - **Choices of bandwidth and sampling**
  - **Higher quantization**
  - **Creative post-pass processing, arraying, landing tone processors, etc.**

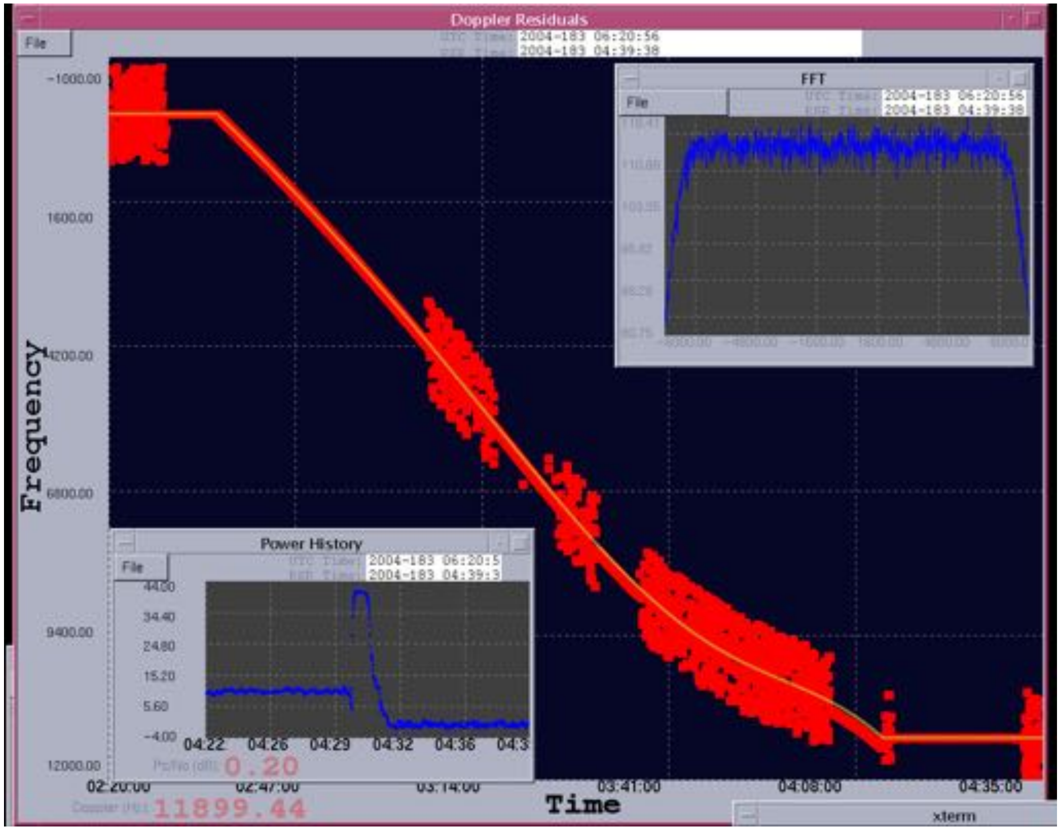
Advanced Tropospheric Calibration

Timing Is Everything



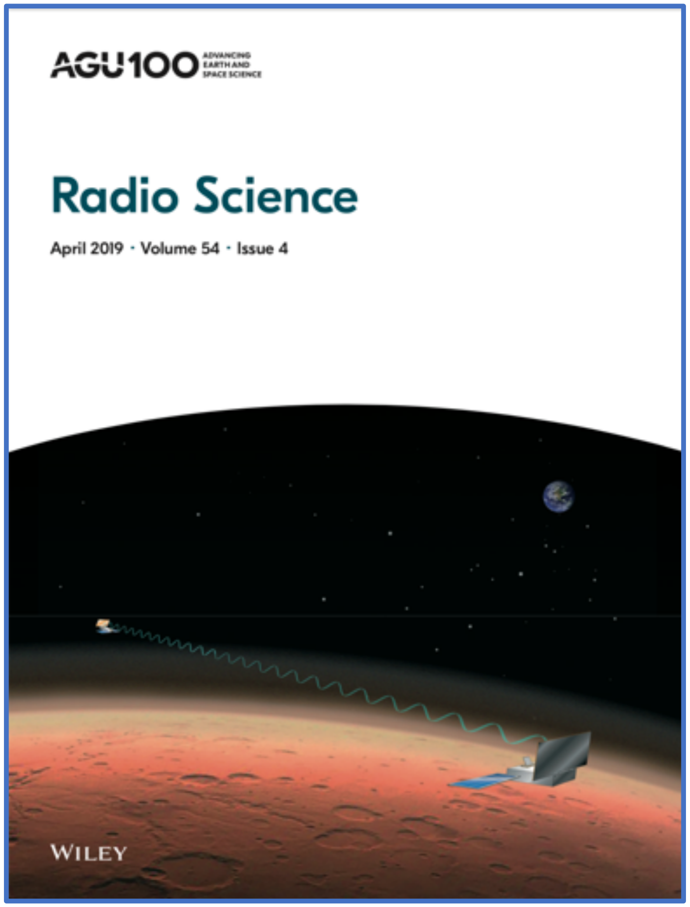
Mission Support Example: Saturn Orbit Insertion

- Handling low signal levels and high dynamics allow system to support:
  - Anomalies and spacecraft in distress
  - Special spacecraft maneuvers
    - Entry, descent and landing
    - Orbit insertion
    - Other
  - Engineering Studies
    - Characterize Ka-links for future telemetry applications
    - Telemetry performance near solar conjunctions
    - RFI analysis



Future Trend: Small Spacecraft Constellations

- "Small spacecraft," "SmallSats," or "CubeSats" ~ 6 to 12 U
- Ride-along small spacecraft can be used to explore the atmospheres, surfaces, interiors, rings, and the environment surrounding planets, moons, as well as asteroids and comets
- Small spacecraft are well suited as small constellations for crosslink occultations, GRAIL-like gravity and interior science, and multiple entry probes
- Placed in orbit
  - Studied extensively for Mars; currently examined for Venus
- Targeted flybys
  - Short lifetime probes for key gravity field measurements
    - Benefit by closeness to body and risk reduction
- Atmospheric entry for in-situ science
  - Entry probes and balloons



Source: https://agupubs.onlinelibrary.wiley.com
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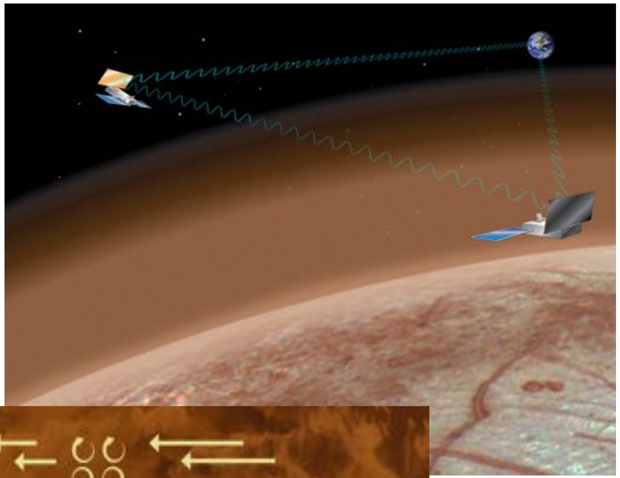
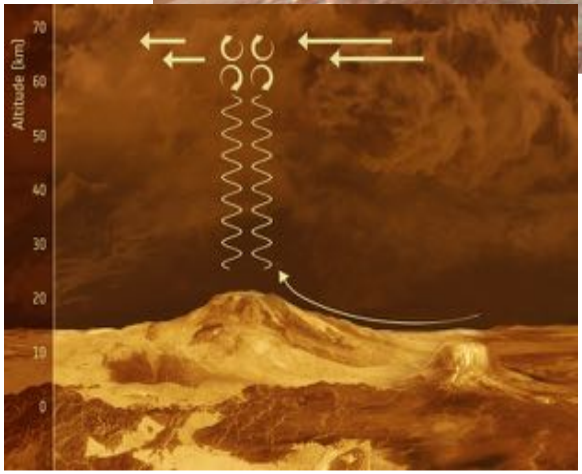
Placed in Orbit

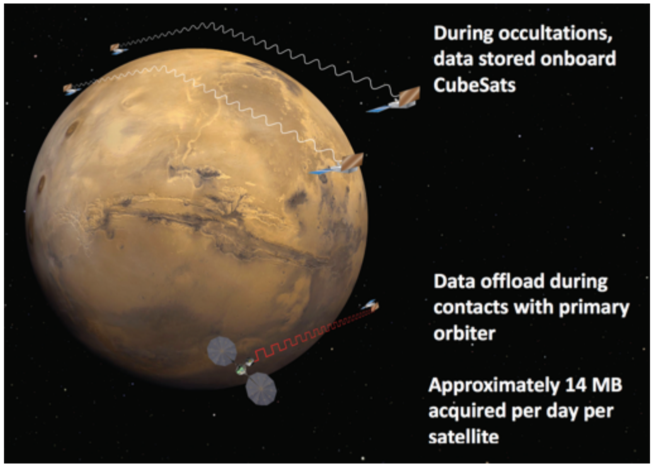
- **Science: Planetary Atmospheric/Ionospheric Structure**
  - High vertical & temporal resolution measurements of atmospheric density, temperature, and ionospheric electron number density (utilizing dual wavelengths) via radio occultations with global coverage
  - **Mission**: 2 or 3 CubeSats in orbits at appropriate altitudes & inclinations to provide frequent line-of-sight for atmospheric occultations
- **Science: Gravitational Fields Interior Structure**
  - High-resolution gravitational field mapping to explore the interior structure and time-varying planetary properties
  - **Mission**: GRAIL with much smaller spacecraft!
- **Science: In-situ Measurements of Planetary Dynamics**
  - Study winds, tides, and waves. 2 or 3 entry vehicles/probes
- **Science: Surface properties and roughness**
  - Signal scattering experiments (bistatic radar) to explore surface and near sub-surface material properties. Small body lander or hoppers





High temporal and spatial resolution properties of thermal tides & geophysical-driven waves could be captured by radio occultations, especially if the SmallSats are placed over a dedicated active location

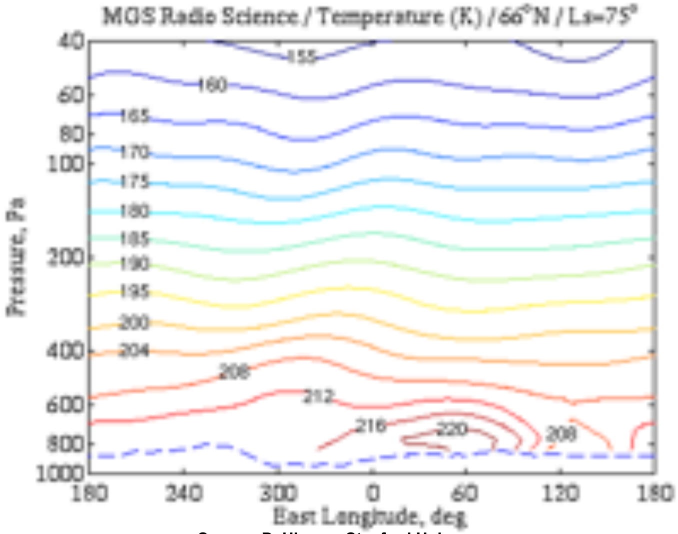
Simulations of Rapid Global Coverage



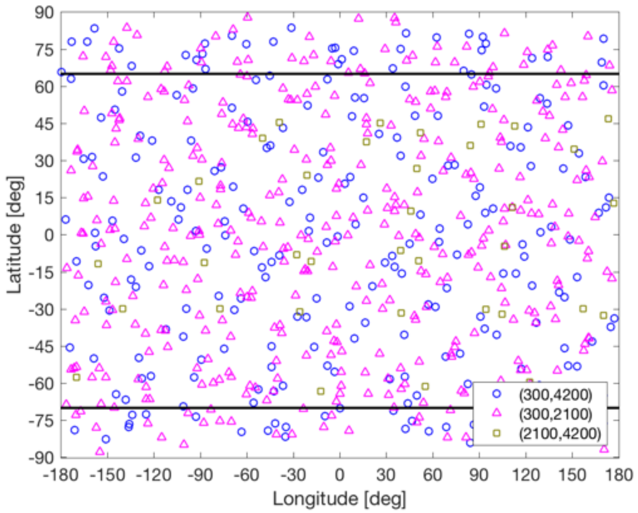
Atmosphere of Mars from Mars Global Surveyor occultations
Coverage in ten years

vs.

Three Mars CubeSats Pairwise occultation locations
One week acquisition time

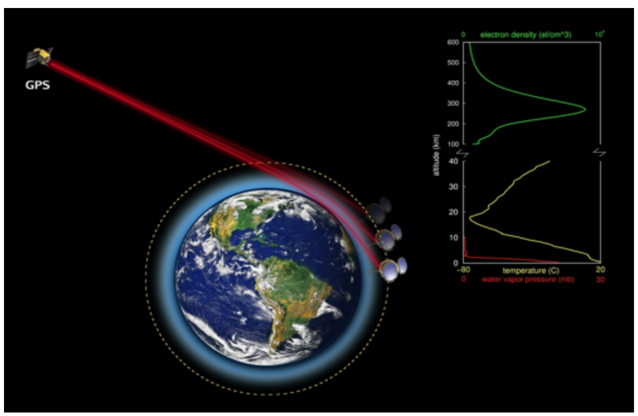


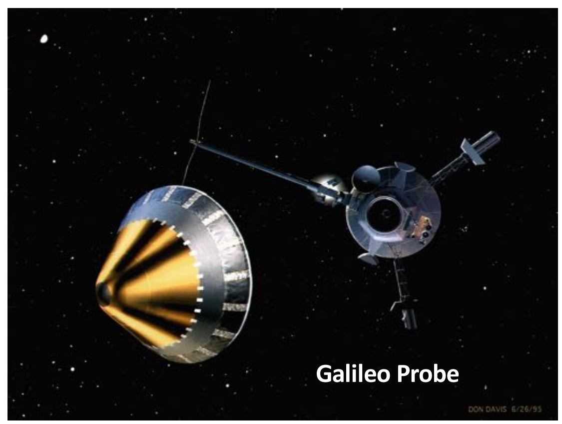
Source: D. Hinson, Stanford Univ.



Planetary Crosslinks Already Demonstrated

- **For Atmospheric radio occultations**
  - **Odyssey to MRO (Mars)**
- **For gravity science**
  - **GRACE (Earth) and GRAIL (Moon)**
- **For the in-situ Doppler wind experiments**
  - **Galileo probe to the Galileo orbiter (Jupiter)**
  - *Huygens to Cassini (Titan) Link failure due to operation error*





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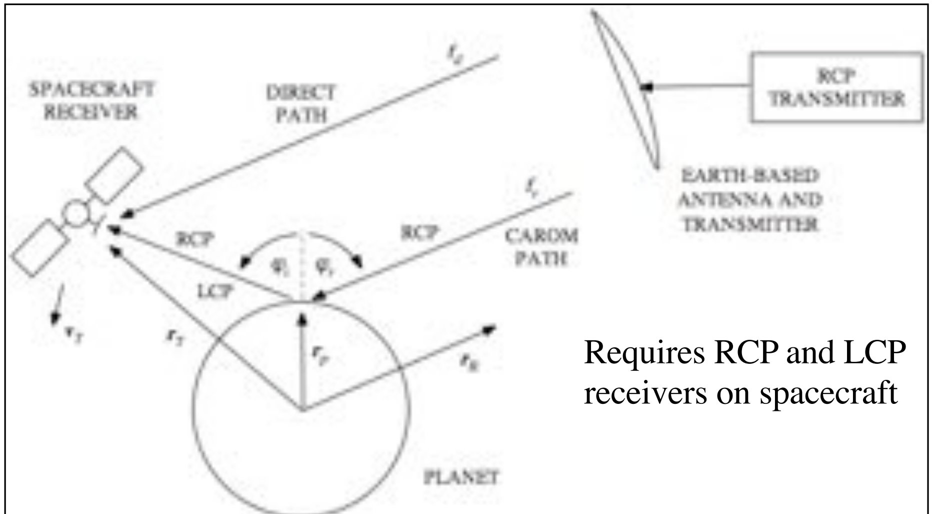
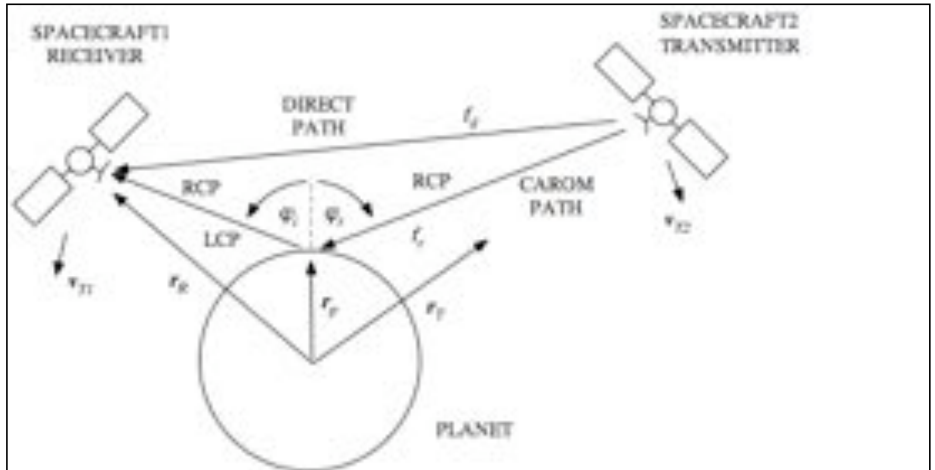
Uplink and Crosslink Bistatic Radar to Spacecraft



Requires RCP and LCP receivers on spacecraft

- Bistatic Radar originally envisaged as uplink; transmitter on Earth and receiver on spacecraft
- Up to 30 dB SNR advantage over 'downlink' (mostly from higher Tx power)
- First uplink surface observations conducted using Mars Odyssey in 2004
- New Horizons Pluto in 2015



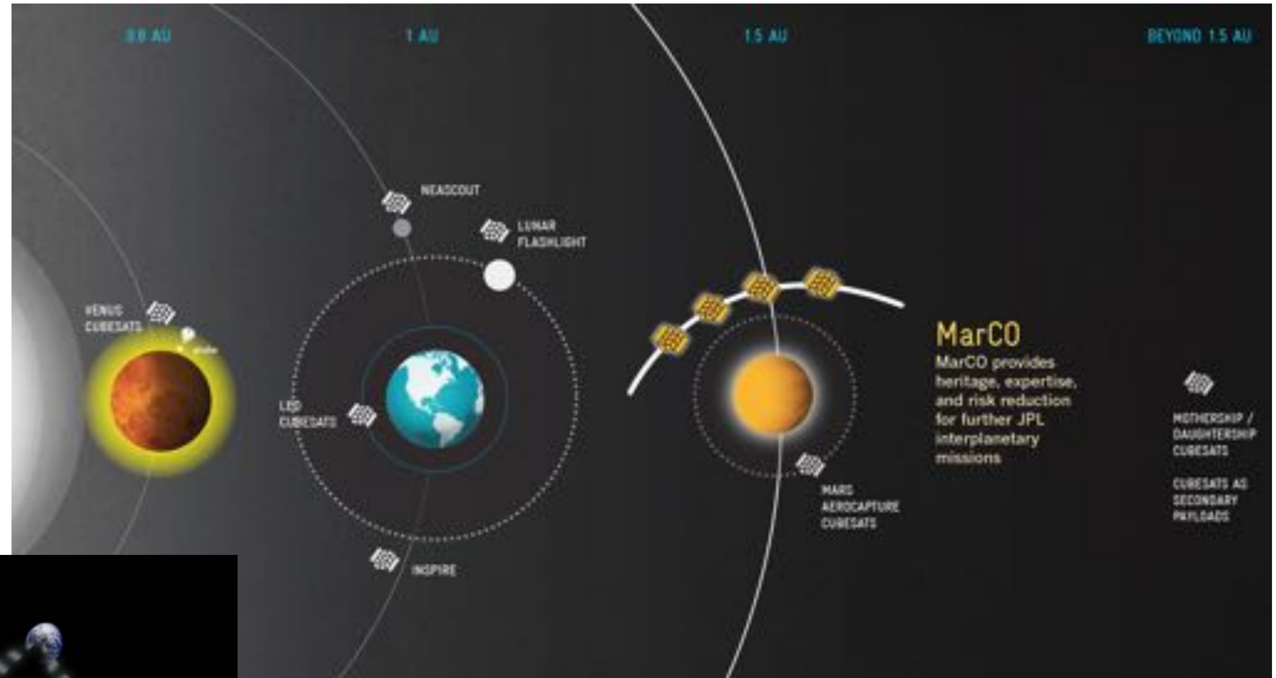
Obviates need for large Earth-based antenna, receiver, and/or transmitter; but requires new investment in science-quality spacecraft radio instrumentation

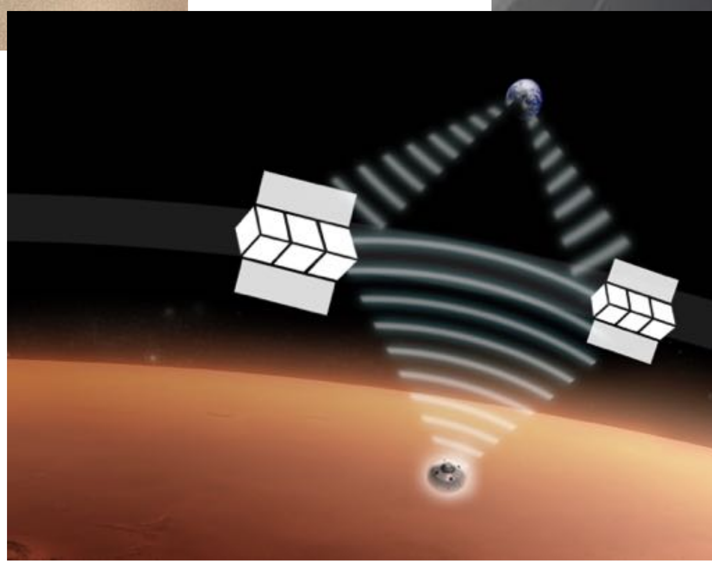
- Two or more spacecraft
- Low-noise receiving environment
- Dual-polarization tunable receivers
- Precision time/frequency references
- High-speed A/D conversion
- Careful planning and synchronization

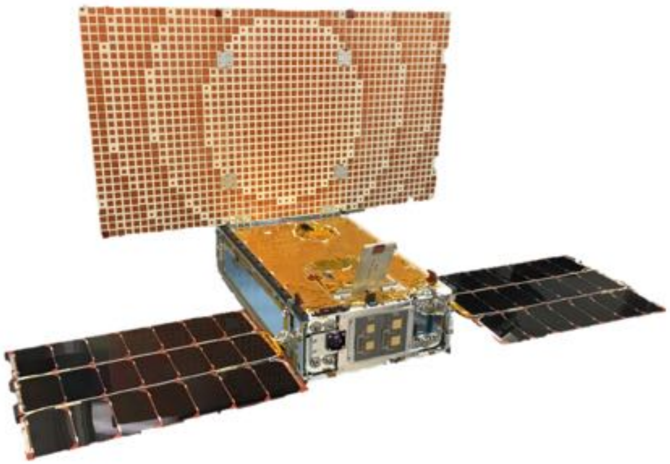
Graphics Credit: R. Simpson

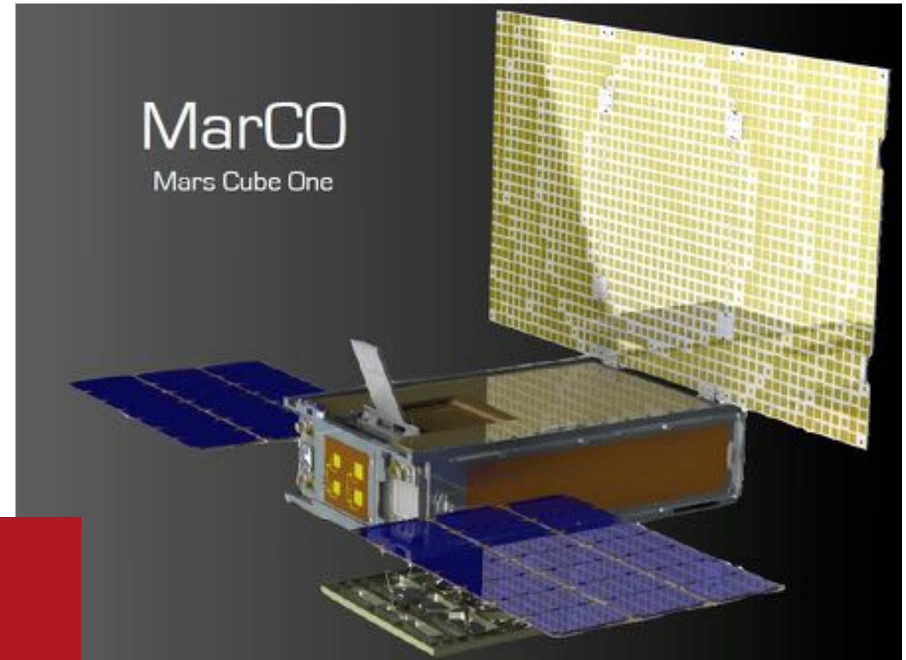
Thank You

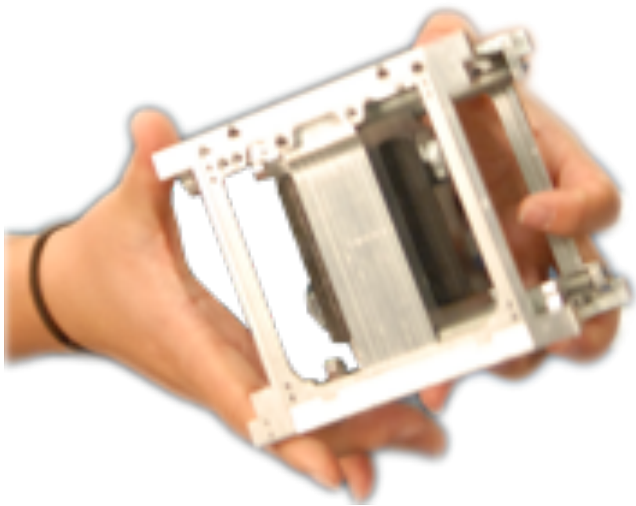
Back-up


1 AU
1.5 AU
BEYOND 1.5 AU
NEASCOUT
LUNAR FLASHLIGHT
VENUS CUBESATS
LEO CUBESATS
INSPIRE
MARS AEROCAPTURE CUBESATS
MarCO
MarCO provides heritage, expertise, and risk reduction for further JPL interplanetary missions
MOTHERSHIP / DAUGHTERSHIP CUBESATS
CUBESATS AS SECONDARY PAYLOADS






MarCO
Mars Cube One

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MARCO
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